

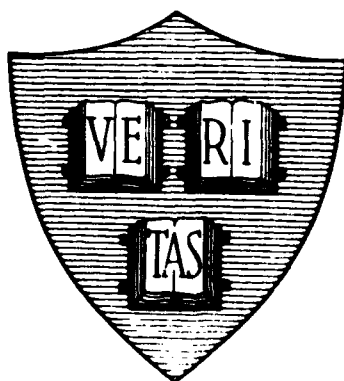
**AD-A253 842**

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100

**Division of Applied Sciences  
Harvard University — Cambridge, Massachusetts**

(1)

**ANNUAL PROGRESS REPORT NO. 106**



**DTIC  
ELECTE  
AUG 10 1992  
S A D**

**JOINT SERVICES ELECTRONICS PROGRAM  
N00014-89-J-1023**

**This document has been approved  
for public release and sale; its  
distribution is unlimited.**

**Covering Period  
August 1, 1991 — July 31, 1992**

**92-21864**



**July 1992**

**92 8 6 052**

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
1a. REPORT SECURITY CLASSIFICATION Unclassified			1b. RESTRICTIVE MARKINGS		
2a. SECURITY CLASSIFICATION AUTHORITY N/A			3. DISTRIBUTION/AVAILABILITY OF REPORT  Unclassified/Unlimited		
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE N/A					
4. PERFORMING ORGANIZATION REPORT NUMBER(S) Annual Progress Report No. 106			5. MONITORING ORGANIZATION REPORT NUMBER(S) Office of Naval Research		
6a. NAME OF PERFORMING ORGANIZATION Harvard University		6b. OFFICE SYMBOL (if applicable)	7a. NAME OF MONITORING ORGANIZATION Office of Naval Research		
6c. ADDRESS (City, State, and ZIP Code) Division of Applied Sciences Harvard University Cambridge, MA 02138			7b. ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, VA 22217		
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Office of Naval Research		8b. OFFICE SYMBOL (if applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-89-J-1023		
8c. ADDRESS (City, State, and ZIP Code) 800 N. Quincy St. Arlington, VA 22217			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.
11. TITLE (Include Security Classification) Annual Progress Report No. 106					
12. PERSONAL AUTHOR(S) Prof. Michael Tinkham					
13a. TYPE OF REPORT Technical		13b. TIME COVERED FROM 8/1/91 TO 7/31/92		14. DATE OF REPORT (Year, Month, Day) July 1992	
15. PAGE COUNT 124					
16. SUPPLEMENTARY NOTATION					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)		
FIELD	GROUP	SUB-GROUP			
19. ABSTRACT (Continue on reverse if necessary and identify by block number)  An annual report of the JSEP (Joint Services Electronics Program) in solid state electronics, quantum electronics, information electronics, control and optimization, and electromagnetic phenomena is presented. Results of the research to date are summarized and significant accomplishments are discussed					
20. DISTRIBUTION/AVAILABILITY OF ABSTRACT <input checked="" type="checkbox"/> UNCLASSIFIED/UNLIMITED <input type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL Prof. Michael Tinkham, Director			22b. TELEPHONE (Include Area Code) (617) 495-3735		22c. OFFICE SYMBOL

**Joint Services Electronics Program**

N00014-89-J-1023

**ANNUAL PROGRESS REPORT NO. 106**

Covering Period

August 1, 1991 — July 31, 1992

The research reported in this document, unless otherwise indicated, was made possible through support extended to the Division of Applied Sciences, Harvard University by the U. S. Army Research Office, the U. S. Air Force Office of Scientific Research and the U. S. Office of Naval Research under the Joint Services Electronics Program by Grant N00014-89-J-1023. Related research sponsored by the Office of Naval Research, the National Science Foundation, the Department of Energy, and by the University is also reported briefly with appropriate acknowledgment.

**DTIC QUALITY INSPECTED 5**

Division of Applied Sciences  
Harvard University  
Cambridge, Massachusetts

Accession For	
NTIS	CRA&I <input checked="checked" type="checkbox"/>
DTIC	TAB <input type="checkbox"/>
Unannounced <input type="checkbox"/>	
Justification .....	
By .....	
Distribution /	
Availability Codes	
Dist	Availability / or Special
A-1	



## ANNUAL PROGRESS REPORT NO. 106

### Joint Services Grant

N00014-89-J-1023

The Steering Committee

### Related Contracts and Grants

MIT-GC-R-102337

R.W. Brockett, Y.C. Ho, J.J. Clark

N00014-86-K-0033

H. Ehrenreich

N00014-89-J-1565

M. Tinkham

N00014-89-J-1592

R.M. Westervelt

N00014-90-J-1093

Y.C. Ho

NSF-CDR-88-03012

Y.C. Ho

NSF-DMR-88-17309

R.M. Westervelt

NSF-DMR-88-58075

E. Mazur

NSF-DMR-89-12927

M. Tinkham

NSF-DMR-89-1486

W. Paul

NSF-DMR-89-20490

H. Ehrenreich, J.A. Golovchenko

E. Mazur, W. Paul, P.S. Pershan,

M. Tinkham, R.M. Westervelt

P.S. Pershan

NSF-DMR-91-13782

J.A. Golovchenko

NSF-DMR-91-11494

Y.C. Ho

NSF-ECS-91-02346

W. Paul

NSF-INT-89-15070

J.J. Clark

NSF-IRI-90-03306

DAAL03-86-K-0171

Y.C. Ho

DAAL03-88-K-0114

E. Mazur

DAAL02-89-K-0097

T.T. Wu

DAAL03-89-G-0076

R.M. Westervelt

DAAL03-91-G-0194

Y.C. Ho

DE-FG02-84-ER40158

T.T. Wu

DE-FG02-88-ER45379

P.S. Pershan

DE-FG02-89-ER45399

J.A. Golovchenko

F19628-91-K-0020

T.T. Wu

AFOSR-90-0248

J.A. Golovchenko

SERI-XX-8-18131-1

W. Paul



# **JOINT SERVICES ELECTRONICS PROGRAM**

August 1, 1991 — July 31, 1992

## **ADMINISTRATIVE STAFF**

### **Grant**

N00014-89-J-1023

### **The Steering Committee**

Prof. R.W. Brockett  
Assoc. Prof. J.J. Clark  
Prof. H. Ehrenreich  
Prof. J.A. Golovchenko  
Prof. Y.C. Ho  
Prof. E. Mazur  
Prof. W. Paul  
Prof. P.S. Pershan  
Prof. M. Tinkham  
Prof. R.M. Westervelt  
Prof. T.T. Wu  
Asst. Prof. W. Yang

## **RESEARCH STAFF**

Dr. R.W. Brockett  
Dr. J.H. Burnett  
Dr. J.J. Clark  
Dr. H. Ehrenreich  
Dr. J.A. Golovchenko  
Dr. Y.C. Ho  
Dr. E. Hsu  
Dr. P.-M. Hui  
Dr. R.W. P. King  
Dr. C.M. Marcus  
Dr. E. Mazur  
Dr. W. Mieher  
Dr. L. Mollamustafaoglu  
Dr. J.M. Myers

Dr. W. Paul  
Dr. P.S. Pershan  
Dr. T. Rabedeau  
Dr. E. Runge  
Dr. M.S. Rzchowski  
Dr. H.-M. Shen  
Dr. R. Sreenivas  
Dr. Z.B. Tang  
Dr. M. Tinkham  
Dr. M. Tuominen  
Dr. R.M. Westervelt  
Dr. T.T. Wu  
Dr. W. Yang



## INTRODUCTION

This report covers progress made during the past year in the work of eleven Research Units funded under the Joint Services Electronics Program at Harvard University. It is broken down into four major divisions of electronic research: *Solid state electronics*, *Quantum electronics*, *Information electronics*, and *Electromagnetic phenomena*. Following the report of the work of each Unit, there is a complete annual report of the associated Publications/Patents/Presentations/Honors. This report also includes a section on *Significant Accomplishments* which contains selected highlights from two of these Units, entitled "Competitive Analog Neural Networks for Translation-Invariant Feature Detection," Research Unit 5, and "A Novel Resonant Array of Parallel Dipoles with Unique and Useful Properties," by Research Unit 11.



## CONTENTS

CONTRACTS AND GRANTS . . . . .	iii
STAFF . . . . .	v
INTRODUCTION . . . . .	vii
CONTENTS . . . . .	ix

### I. SOLID STATE ELECTRONICS

1. Electronic Theory of Semiconductor Alloys and Superlattices. <i>H. Ehrenreich</i> . . . . .	1
<i>Annual Report of Publications/Patents/Presentations/Honors</i> . . . . .	9
2. Pressure Dependence of Photoluminescence and Photoluminescence/ Excitation in Quantum Wells and Superlattices. <i>J.H. Burnett, H.M. Cheong, and W. Paul</i> . . . . .	11
<i>Annual Report of Publications/Patents/Presentations/Honors</i> . . . . .	17
3. X-Ray Surface Characterization. <i>I.M. Tidswell, T. Rabedeau, and P.S. Pershan</i> . . . . .	18
<i>Annual Report of Publications/Patents/Presentations/Honors</i> . . . . .	23
4. Superconducting Josephson Junction Arrays. <i>M.S. Rzchowski, L.L. Sohn, T.S. Tighe, and M. Tinkham</i> . . . . .	24
5. Single-Electron Tunneling Devices. <i>A. Hanna, M. Tuominen, J. Hergenrother, and M. Tinkham</i> . . . . .	26
<i>Annual Report of Publications/Patents/Presentations/Honors</i> . . . . .	29
6. Neural Networks. <i>F.R. Waugh, R. Seshadri, C. Marcus, and R. M. Westervelt</i> . . . . .	31
<i>Annual Report of Publications/Patents/Presentations/Honors</i> . . . . .	37
7. Structural and Dynamical Studies of Semiconductor Interfaces and Sur- faces. <i>J. A. Golovchenko</i> . . . . .	40
<i>Annual Report of Publications/Patents/Presentations/Honors</i> . . . . .	43

## II. QUANTUM ELECTRONICS

1. Femtosecond Nonlinear Optical Interactions.  
E. Mazur, E. Glezer, Y. Siegal, and J.K. Wang . . . . . 45
2. Interactions with Ultrashort Laser Pulses.  
E. Mazur, C.Z. Lü, S. Deliwala, and J. Goldman . . . . . 47
- Annual Report of Publications/Patents/Presentations/Honors* . . . . . 50

## III. INFORMATION ELECTRONICS: CIRCUITS AND SYSTEMS

1. Analog VLSI and Principal Component Analysis.  
R.W. Brockett, J.J. Clark, and W. Yang . . . . . 53
2. Analog VLSI Implementation of the Eigenvalue Finder.  
R.W. Brockett, J.J. Clark, and W. Yang . . . . . 54
3. Toda Lattice Sorter.  
R.W. Brockett, J.J. Clark, and W. Yang . . . . . 56
4. Massively Parallel Processor for Eigenvalue Computation.  
R.W. Brockett, J.J. Clark, and W. Yang . . . . . 57
5. Infinitesimal Perturbation Analysis.  
R.W. Brockett, J.J. Clark, and W. Yang . . . . . 58
- Annual Report of Publications/Patents/Presentations/Honors* . . . . . 60
6. Ordinal Optimization  
Y. C. Ho, R. Sreenivas, Z.B. Tang, L. Mollamustafaoglu . . . . . 61
7. Pulse-Frequency Analog Computing.  
Y.C. Ho . . . . . 61
- Annual Report of Publications/Patents/Presentations/Honors* . . . . . 63

## IV. ELECTROMAGNETIC PHENOMENA

1. Electromagnetic Field of Dipoles and Patch Antennas on Microstrip.  
R.W.P. King . . . . . 67
2. The Circuit Properties and Complete Fields of Wave Antennas and Arrays.  
R.W.P. King . . . . . 69

3. The Propagation of a Gaussian Pulse in Sea Water. R.W.P. King, B.H. Sandler, and M. Owens . . . . .	71
4. The Propagation of a Low-Frequency Burst in Sea Water. R.W.P. King, B.H. Sandler, and M. Owens . . . . .	74
5. The Propagation of a Radar Pulse in Sea Water. R.W.P. King, T.T. Wu, M. Owens, and B.H. Sandler . . . . .	76
6. Radiation of Electromagnetic Waves from a Tether in the Ionosphere to the Surface of the Earth. R.W.P. King . . . . .	78
7. Electromagnetic Fields of Vertical and Horizontal Magnetic Dipoles in and over the Sea. R.W.P. King and M. Owens . . . . .	79
8. The Detection of Dielectric Spheres Submerged in Water. R.W.P. King and S.S. Sandler . . . . .	80
9. Lateral Electromagnetic Waves (book). R.W.P. King, M. Owens, and T.T. Wu . . . . .	82
10. Theoretical Study of Electromagnetic Pulses with a Slow Rate of Decay. T.T. Wu, J.M. Myers, H.-M. Shen, R.W.P. King, and V. Houdzoumis . .	83
11. Experimental Study of Electromagnetic Pulses with a Slow Rate of Decay. H.-M. Shen, R.W.P. King, and T.T. Wu . . . . .	85
12. Lessons for Pulsed-Array Radar from Quantum Light Detection. J.M. Meyers, F.H. Madjid, and T.T. Wu . . . . .	86
13. The Launching of High-Power Microwave Pulses from a Relativistic Klystron Amplifier. T.T. Wu, R.W.P. King, J.M. Meyers, and H.-M. Shen . . . . .	88
14. Improved Analysis of the Resonant Circular Array. G. Fikioris, D.K. Freeman, R.W.P. King, and T.T. Wu . . . . .	90
15. Experimental Studies of Resonances in a Large Circular Array. G. Fikioris . . . . .	92
16. Properties of Closed-Loop Arrays of Quantum Mechanical and Elec- tromagnetic Interactions. D.K. Freeman and T.T. Wu . . . . .	94
17. Experimental Study of a Noncircular Array. T.T. Wu, R.W.P. King, and H.-M. Shen . . . . .	97
18. Plasma Waveguide: A Concept to Transfer EM Energy in Space. H.-M. Shen . . . . .	99
<i>Annual Report of Publications/Patents/Presentations/Honors . . . . .</i>	<i>101</i>

## V. SIGNIFICANT ACCOMPLISHMENTS REPORT

1. Competitive Analog Neural Networks for Translation-Invariant Feature Detection.  
*F.R. Waugh and R.M. Westervelt . . . . . 105*
2. A Novel Resonant Array of Parallel Dipoles with Unique and Useful Properties.  
*R.W.P. King, T.T. Wu, D.K. Freeman, G. Fikioris, and H.-M. Shen . . 107*

# I. SOLID STATE ELECTRONICS

## Personnel

Prof. H. Ehrenreich  
Prof. J.A. Golovchenko  
Prof. W. Paul  
Prof. P.S. Pershan  
Prof. M. Tinkham  
Prof. R.M. Westervelt  
Dr. J.H. Burnett  
Dr. E. Hsu  
Dr. P.-M. Hui  
Dr. C.M. Marcus  
Dr. T. Rabedeau  
Dr. E. Runge  
Dr. M.S. Rzchowski  
Dr. M. Tuominen

Mr. N. Anand  
Mr. H.M. Cheong  
Mr. C. Grein  
Mr. A. Hanna  
Mr. J. Hergenrother  
Mr. I.-S. Hwang  
Mr. S. Kosowsky  
Ms. R. Seshadri  
Ms. L.L. Sohn  
Mr. S.K. Theiss  
Mr. I.M. Tidswell  
Mr. T.S. Tighe  
Mr. F.R. Waugh  
Mr. P.M. Young

### **I.1 Electronic Theory of Semiconductor Alloys and Superlattices. H. Ehrenreich, Grant N00014-89-J-1023; Research Unit 1.**

During the past year the theoretical research efforts of this group, consisting of C. Grein, P.M. Hui, E. Runge, P.M. Young and H. Ehrenreich, have focussed on 1) excitons and interband transitions in III-V semiconductor superlattices, 2) the response and transit times in quantum well structures, 3) phonon assisted transport through double barrier resonant tunneling structures and 4) Auger processes in GaInSb/InAs and HgCdTe IR detectors. This year's research output in terms of published papers was diminished because of H. Ehrenreich's involvement with the new Federal Program on Materials. Ehrenreich spent much of the fall 1991 at the White House as Consultant to Presidential Science Advisor D.A. Bromley and helped to formulate plans for implementing this initiative. At Bromley's request he prepared a white paper entitled *The Proposed Federal Program in Materials Science and Technology: Comments and Views* (1991, unpublished).

## A. Excitons and Interband Transitions in III-V and II-VI Semiconductor Superlattices

The fundamental absorption in InGaAs/InAlAs and GaAs/GaAlAs superlattices has been calculated quantitatively using a superlattice  $K \cdot p$  theory. Electron-hole Coulomb interactions yielding excitons and interband transition enhancement associated with the Sommerfeld factor are incorporated in the theory. The Coulomb interaction is treated within an independent subband approximation that associates each exciton with a single conduction and a single valence band. This approach, together with a simple model representing the superlattice Wannier functions which is both simple and accurate, leads to an analytic form for the electron-hole interaction that permits calculation of the exciton wavefunction, binding energy and optical absorption without resorting to a variational approach. The only input consists of constituent bulk parameters, band offsets and strains as described by deformation potentials. The calculations require only 10 minutes of CPU time on a SUN system, and yield optical structure within 2-3 meV and absolute absorption coefficients within 10% of experimental results for all but one of the 12 InGaAs/InAlAs and GaAs/GaAlAs samples analyzed. The experimental optical absorption data and the sample quality chosen for comparison with the theory are believed to be the most reliable available at the present time. The modest computer requirements permit an investigation of the behavior of optical structure as a function of band offsets and other interface parameter and therefore allows estimates of physically important quantities of relatively unexplored heterostructure systems, for example II-VI superlattices [1].

This same approach has been applied to wide band gap II-VI superlattices of possible importance to blue-green laser applications. The excitonic and interband optical absorption in ZnCdSe/ZnSe and ZnCdTe/ZnTe have been explored utilizing the data of A. Nurmikko's group at Brown University. A paper in preparation describes the results of this work [2]. The II-VI materials are distinguished from their III-V

counterparts in that valence band offsets tend to be smaller, excitons are relatively strongly bound and have a smaller spatial extension, and that lasing action involves recombination from excitons rather than band states. Systematic investigation of these results provides some guidance as to the magnitude of band offsets which are not yet known with sufficient accuracy. The small valence band offsets suggest that the Te-based superlattices may fall into a weak type II regime. Variational calculations have been performed to examine the behavior of excitons in this regime. These calculations have also been very helpful in providing confidence that the simpler binding energy nonvariational calculations mentioned above are quantitatively accurate for type I superlattices. Because of the considerable lattice mismatch that characterizes these superlattices, the proper incorporation of strain effects is important.

The effects of applied electric and magnetic fields on superlattice excitons have also been systematically investigated. In the magnetic field case, the weak field limit, for which the cyclotron energy is less than the mini-band gap, is adequate for our purposes since the weak field limit extends to 10–20 Tesla. The present formalism suffices for the interpretation of most experimental data of technical interest. The exciton structure is observed to pass smoothly to the regime in which a description in terms of Landau levels is more appropriate. Theory and experiment are found to agree within 0.5 meV for the energies of the four lowest exciton levels in fields extending to 8 Tesla in two different InGaAs/GaAs quantum well samples. In a GaAs/GaAlAs superlattice system correspondingly good agreement is found for the three lowest levels for fields up to 20 Tesla. The exciton binding energy increases as a function of field, an effect which is most pronounced for the lowest levels.

Electric fields tend to localize the electron and hole along the direction of the field and induce the formation of a Stark ladder in the superlattice at fields above about  $10^4$  V/cm. The present formalism is applicable to fields extending up to  $10^5$  V/cm. For higher fields the independent sub-band approximation breaks down due to

interband tunneling. The agreement between theory and experiment is excellent for two GaAs/GaAlAs superlattices that have been examined up to fields of 120 kV/cm. The binding energy of the strongest exciton is enhanced by the field due to the Stark localization of the electron and hole within the same well.

These results represent part of P.M. Young's Ph.D. thesis which is almost completed. They will be ready for publication shortly.

Observed optical structure in GaAs/GaAlAs heterostructures that cannot be explained by our calculations has suggested the possibility of unintentionally induced quantum well asymmetry in these structures. Such asymmetries would break the usual optical selection rules and result in additional structure. Most probably these asymmetries are associated with unintentionally introduced electric fields created, for example, through doping imbalance between the buffer and capping layers of a heterostructure. They could also be created by dangling bonds associated with the intentional miscut that is introduced during superlattice growth. Another likely possibility is that compositional gradients either in the barriers, the wells or in both may be introduced as a result of the MBE growth process. For example, the flux of the Al deviates briefly from its nominal value when shutters are open or closed resulting in a composition gradient and a resulting field. All observed structure can be explained quantitatively by postulating fields of the order of  $10^4$  V/cm. The results have been accepted for publication in *Applied Physics Letters* [3]. The simple and versatile calculational techniques for calculating optical properties that have been developed are likely to be useful for a variety of applications, among them, the characterization of actual device structures.

#### References:

1. P.M. Young, P.M. Hui and H. Ehrenreich, *Phys. Rev. B* **44**, 12 969 (1991).
2. M. Ziegler, E. Runge, P.M. Young and H. Ehrenreich (to be published).
3. P.M. Young and H. Ehrenreich, *Appl. Phys. Lett.* (to be published).

## B. Response and Transit Times in Quantum Well Structures

The electrical properties of double barrier quantum well and other types of nanostructures are of considerable importance because of their potential applicability in computer applications. For example double barrier quantum wells (DBQW) are prototypical circuit components in cellular automata in which each cell is required to have a high frequency response and to be decoupled from all but its nearest neighbors. Effective decoupling can be achieved if wavefunction coherence between adjacent cells is small. The question addressed in the present work concerns the relative importance of coherent vs. sequential tunneling. Phase coherence effects are not present in the latter process. In recently published work [1,2] the response of a bias DBQW structure to a small ac voltage is calculated using nonequilibrium Green's function techniques. The tunneling is shown to be predominantly sequential in InGaAs/InAlAs structures due to only well alloy scattering which is described in the coherent potential approximation. Of particular interest is the fact that the transit or dwell time, which has been measured in detail by Chemla and collaborators, is numerically very similar to the technologically more significant ac response time, which is far more difficult to measure. The ac response time, which we have introduced, provides an explicit measure of the frequency response of nanostructures involving tunneling and therefore promises to be generally useful. Its value is about  $\tau = 50$  ps for the structures investigated.

These quantum transport calculations have been extended to investigate the noise properties. In the simplest case of small external bias, thermal Johnson noise is predominant. Shot noise is predominant for larger bias when the quantum well structure as a whole is no longer in thermal equilibrium. At high bias voltages, frequency independent shot noise results for systems with appreciably asymmetric barriers. However, in the case of barriers having about the same transparency, the noise current power spectrum is frequency dependent as a result of structure-induced correlations between subsequent electron tunneling events. This frequency dependence is characterized by

the same ac response time which limits the high speed performance of such devices. The frequency dependence of the noise current power spectrum reflects temporal correlations between electrons tunneling into and out of the well [3].

Electron-electron interactions have been considered in connection with a one-dimensional model describing resonant tunneling through a quantum dot characterized by a ground state and a single accessible excited state. These interactions can dominate the device behavior of nanostructures operated at low voltage. In order to understand the associated energy and time scales the dynamic response is evaluated within the context of a Hubbard Hamiltonian using nonequilibrium Green's function techniques.

#### **References:**

1. E. Runge and H. Ehrenreich, *Phys. Rev. B* **45**, 9145 (1992).
2. E. Runge and H. Ehrenreich, *Annals of Physics* (accepted for publication).
3. E. Runge (to be published).

#### **C. Phonon Assisted Transport Through Tunneling Structures**

The goal of this research is to understand the origin of the weak replica peak observed in the dc I-V curves of high quality DBQW structures. This peak, due to optical phonons, appears at high voltages greater in magnitude than the main resonant tunneling peak. A more realistic phonon model involving confined modes with dispersion is introduced to describe confined and interface optical modes. The present calculations, based on the same kind of transport calculations described in Section B above, reproduce the observed position and magnitude of the replica peak and confirm its origin as arising from inelastic scattering of electrons due to quantum well vibrational, in particular, interfacial modes. The use of the virtual crystal bulk phonon spectrum in these calculations would spoil the good agreement with experiment. While confined phonon modes have been previously observed Raman scattering experiments, their

importance in transport properties has been previously unappreciated [1].

**Reference:**

1. C. Grein, E. Runge and H. Ehrenreich (manuscript in preparation).

**D. Auger Processes in GaInSb/InAs and HgCdTe Infrared Detectors and Quantum Well Lasers**

The primary focus of this work is on GaInSb/InAs superlattice IR detectors which potentially could operate at a longer wavelength with reduction in tunneling noise and suppression of Auger recombination. Because the system involves III-V rather than II-VI compounds it may be possible to fabricate such structures more reproducibly and therefore with higher yields. The goal of this research is the theoretical evaluation of "ideal" device characteristics. This involves calculation of the electronic structure, optical absorption coefficients, a quantum transport theory for evaluating electron and hole currents, and a quantitative assessment of electrical noise.

Substantial funding for this work has been requested from DARPA/ONR. Since many of its results are also applicable to quantum well lasers, the quantum efficiency of such devices will also be explored under JSEP auspices.

As may be gathered from the research efforts described above, many of the techniques for undertaking this program are already at hand. At present we are investigating nonradiative Auger processes for the GaInSb/InAs superlattice IR detector on the basis of a realistic superlattice band structure. We have obtained preliminary results and identified the regions of K-space predominantly responsible for radiationless recombination. The computer code under development is believed to be the most quantitative tool for investigating Auger processes presently available.

The results obtained are being compared to HgCdTe superlattice and alloy IR detectors. Preliminary results indicate that the III-V system, which is being investi-

gated extensively by T.C. McGill's group at Caltech and also at Hughes, is at least comparable to HgCdTe alloy detectors. The preliminary results for HgCdTe superlattices are sufficiently surprising that comments concerning them will be deferred to a later date [1].

**Reference:**

1. C. Grein, P.M. Young, H. Ehrenreich and T.C. McGill (submitted to MTC Workshop, Boston, 1992).

**ANNUAL REPORT OF  
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

**a. Papers Submitted to Refereed Journals (and not yet published)**

P.M. Young and H. Ehrenreich, "Evidence for Quantum Well Asymmetry in Optical Absorption," *Appl. Phys. Lett.* (Partially supported by N00014-86-K-0033, Fannie & John Hertz Foundation)

E. Runge and H. Ehrenreich, "Non-Equilibrium Transport in Alloy Based Resonant Tunneling Systems," *Annals of Physics*. (Partially supported by N00014-86-K-0033)

**b. Papers Published in Refereed Journals**

P.M. Young, P.M. Hui and H. Ehrenreich, "Excitons and Interband Transitions in III-V Semiconductor Superlattices," *Phys. Rev. B* **44**, 12 969 (1991). (Partially supported by N00014-86-K-0033, Fannie & John Hertz Foundation)

E. Runge and H. Ehrenreich, "Response and Transit Times in Quantum-Well Structures," *Phys. Rev. B* **34**, 9145 (1992). (Partially supported by N00014-86-K-0033)

**c. Books (and sections thereof) Submitted for Publication**

H. Ehrenreich, "Solid State Physics," an article in *Academic Press Dictionary of Science*, in press.

H. Ehrenreich and D. Turnbull, editors, *Solid State Physics*, Vols. **46** (Academic Press, 1993).

**d. Books (and sections thereof) Published**

H. Ehrenreich and D. Turnbull, editors, *Solid State Physics*, Vols. **44**, **45** (Academic Press, 1991).

**g. Invited Presentations at Topical or Scientific/Technical Society Conferences**

H. Ehrenreich, "Defects and Optoelectronic Properties of Semiconductor Heterostructures," DARPA, July 1991.

H. Ehrenreich, Symposium in honor of Rudenstine Inauguration, October 1991.

H. Ehrenreich, "Advanced Materials and Processing Program: The Federal Materials Initiative," National Materials Advisory Board, November 1991.

H. Ehrenreich, "The New Federal Program in Materials: An Observer's View," Condensed Matter Seminar, Harvard University, February 1992.

H. Ehrenreich, "The American Physical Society's Standards for Professional Conduct," AAAS, Chicago, February 1992. (Presented by R.N. Werthamer)

E. Runge and H. Ehrenreich, "Characteristic Time Scales for Transport in Double Barrier Well Systems," 1992 March Meeting of the American Physical Society, March 16-20, 1992.

P.M. Young and H. Ehrenreich, "Effects of Quantum Well Asymmetry on Optical Absorption," 1992 March Meeting of the American Physical Society, March 16-20, 1992.

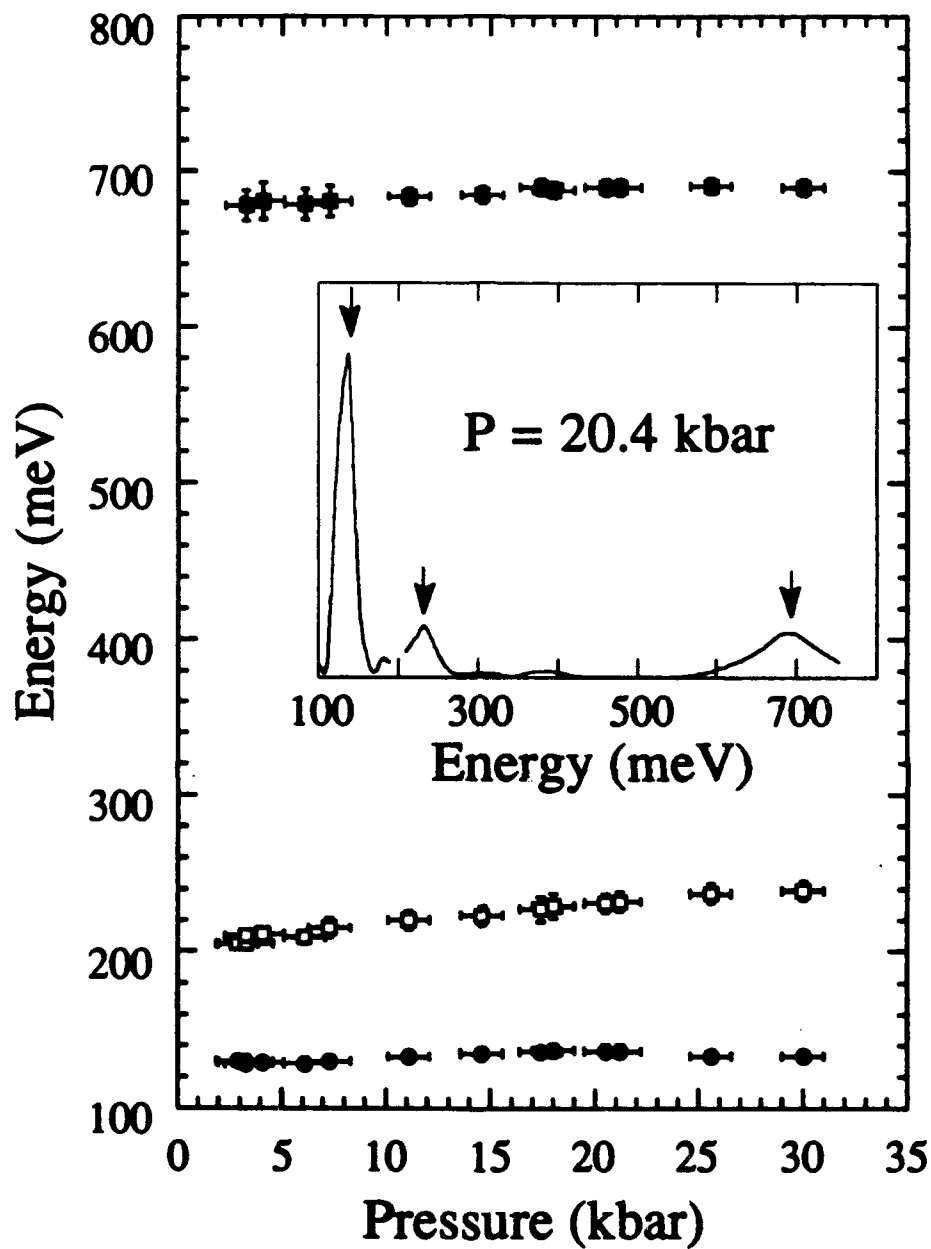
**I.2 Pressure Dependence of Photoluminescence and Photoluminescence Excitation in Quantum Wells and Superlattices.** J.H. Burnett, H.M. Cheong, and W. Paul, Grant N00014-89-J-1023; Research Unit 2.

Using hydrostatic pressure measurements, we have obtained information on Group III-Group V and Group II-Group VI quantum well and superlattice systems, which have significant relevance to their properties at atmospheric pressure. These results are firsts of their kind, and we believe they demonstrate the utility of hydrostatic pressure measurements for understanding the properties of these systems.

**A. Group II-Group VI Systems**

In the last report, we reported an initial measurement of the photoluminescence (PL) of a HgTe/CdTe superlattice (SL) sample at pressures up to 15 kbar at 80 K in an effort to test the current theory on the superlattice band structure of this system. We have completed this project with an extensive set of measurements on another sample at pressures up to 30 kbar. Three major PL peaks are observed in the 100-700 meV range. Figure I.1 shows the pressure dependences of these peaks. The most prominent peak at  $\sim 130$  meV has a pressure coefficient of  $\lesssim 1$  meV/kbar as reported in the previous report. The calculated energies for the three lowest optical transitions in the SL at zero pressure are close to the energies of these peaks, though PL from the two higher energy transitions would not be expected to be observable at 80 K. The higher energy PL peaks, which have similar pressure coefficients (1-2 meV/kbar) as the lowest energy one, are not from the barrier material (CdTe) or from the substrate (CdZnTe), for these peaks were absent in the PL spectra of these materials.

Mr. Paul Young of Prof. Ehrenreich's group has carried out calculations of the pressure dependence of the SL bands within an envelope function approximation (EFA) based on the eight band Kane model, using a valence band-offset ( $\Delta$ ) value of 350 meV. Calculations indicate that the SL band gap increases with pressure at a rate of  $\sim 6.5$  meV/kbar near zero pressure and this rate increases to  $\sim 8$  meV/kbar



**Figure 1.1.** Pressure dependences of the three most prominent photoluminescence peaks from a HgTe/CdTe sample. The inset shows a typical luminescence spectrum, taken at 20.4 kbar. All three peaks have pressure coefficients of 1–2 meV/kbar.

when the pressure reaches 20 kbar. Varying the input parameters within reasonable ranges changes the pressure dependences by less than 10%. A small  $\Lambda$  (40 meV) decreases the pressure dependence by less than 10%. The next lowest energy transitions have similar pressure dependences.

The pressure dependence of the SL band gap of  $\geq 6$  meV/kbar, calculated in the EFA, is far outside the error bars of the measured pressure dependence of the main peak,  $< 1$  meV/kbar. The disagreement between theory and experiment suggests at least one of three possibilities. First, the EFA may be inappropriate to determine the band gap and its pressure dependence. This approximation has been effective in determining the band gap and its pressure dependence for GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  heterostructures, but it may not be valid in describing HgTe/CdTe SL's due to the unusual band structure of HgTe.

Second, the assignment of the strong PL peak at atmospheric pressure to the fundamental SL band gap may be incorrect. Because some of the SL bands are so-called "quasi-interface bands," which have large probability densities at the HgTe/CdTe interface where a large number of interface defects also exist, the fundamental PL may not be strong enough to be seen and the observed PL may be defect luminescence. This is supported by the fact that the PL peak and the absorption edge have different temperature dependences. If this is the case, the PL of HgTe/CdTe may have been generally misidentified in the previous studies. Absorption measurements as a function of pressure would be a decisive test of this possibility. However, it should be noted that generally, defect luminescence peaks are lower in energy than the band gap luminescence, and pressure dependences of defect luminescence peak energies are usually similar to that of the band gap.

Third, one of the assumptions ancillary to the use of the EFA may be incorrect. This could be the assumption that it is proper to ignore the possibility that a defected atomic arrangement at the HgTe/CdTe interface is determining one or other of the

band edge states. It could also be the assumption that  $\Lambda$  at ambient pressure is 350 meV, although this assumption is currently thought to be firmly based. And finally, the assumption of pressure independence of  $\Lambda$  could be wrong. Even though this assumption is generally believed to be valid, with some theoretical support, there has been no experimental proof, and there has been a suggestion of a temperature dependence of  $\Lambda$ . Our calculations of the effect due to the pressure dependence of  $\Lambda$ , however, indicate that to reduce the pressure dependence of the gap to 4 and 1 meV/kbar,  $\Lambda$  has to increase by 15 and 30 meV/kbar, respectively, which seems unreasonably high.

We plan to measure the absorption spectra as a function of pressure. This would eliminate the question of whether the PL is from the transitions between the SL bands. If the absorption has the same pressure dependence as the PL, then the validity of the EFA and/or its ancillary assumptions will have to be reconsidered.

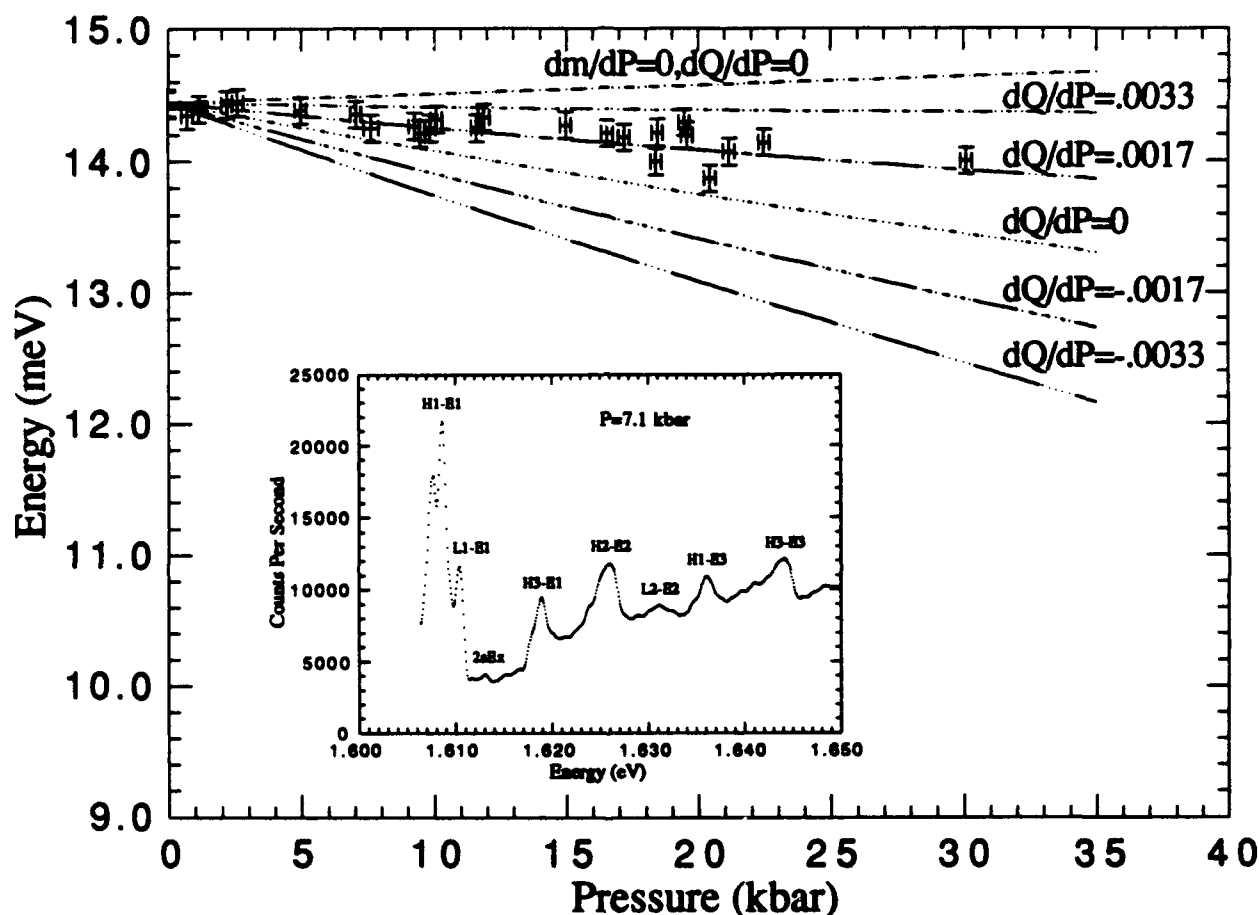
## **B. Group III-Group V Systems**

One of the most important parameters for understanding and designing heterostructure systems is the relative energy of the conduction band (CB) edges at the junctions between the materials, the conduction band offset. For the GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  system, probably the most reliable value determined for this parameter,  $Q_{CB}\Delta E_g = 0.69\Delta E_g$  where  $\Delta E_g$  is the band gap difference, was determined by hydrostatic pressure measurements, by measuring the pressure at which the  $X$  band of the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer crosses the CB minimum of the GaAs layer, resulting in a separation of the electron and holes, and thus a dramatic reduction of the photoluminescence intensity [1]. However, this value depends on one crucial assumption, namely that the band offset is itself independent of pressure. Until now there has been no direct evidence for this assumption. We have now completed preliminary measurements on an experiment to put this assumption to direct test.

To determine the pressure dependence of the conduction band offset, we have measured the harmonic oscillator energy levels of a 1000 Å-wide  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  parabolic quantum well, using photoluminescence excitation (PLE) spectroscopy, as a function of hydrostatic pressure up to 35 kbar. The sample was grown and characterized by Professor A. Gossard at the University of California, at Santa Barbara, CA. A typical PLE spectrum of the parabolic well, here taken at 7.1 kbar, is shown in the inset of Figure I.2, with the principal transition labeled. The harmonic oscillator spacing is obtained from differences in the transition energies. In a simple model the harmonic oscillator spacing is given by:

$$\hbar\omega = \sqrt{\frac{8Q_{CB}\Delta E_g}{L_z^2 m_e^*}},$$

where  $L_z$  is the width of the parabolic well,  $\Delta E_g$  is the difference between the band gap energies at the edge and the center of the well,  $m_e^*$  is the average electron effective mass, and  $Q_{CB}$  is the fraction of the band gap difference in the conduction band. Since  $\hbar\omega$  depends directly on  $Q_{CB}$ , we can directly determine the pressure dependence of  $Q_{CB}$  by measuring  $\hbar\omega$  as a function of pressure. Our measurement of the pressure dependence of  $\hbar\omega$  is shown in Figure I.2. Also included are calculations for the pressure dependence of  $\hbar\omega$ , including the pressure effects on  $L_z$  and  $m_e^*$ , for several assumed pressure dependences of the band offset  $Q_{CB}$ ,  $dQ_{CB}/dP$  (1/kbar). (In the top curve the pressure dependence of the effective mass is neglected.) Our measurements indicate that  $Q_{CB}$  changes less than 7% for pressures from 0 to 35 kbar. If these results are confirmed on further measurements, it supports the validity of the value for the band offset determined by pressure measurements [1]. It also has significance on the role of strain on the band offsets in strained layer superlattices.



**Figure 1.2.** Pressure dependence of the conduction band harmonic oscillator spacing of a 1000 Å  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  parabolic well, determined by measuring the pressure dependence of the energy difference between the photoluminescence peaks H1-E3 and H1-E1 shown in the inset. The lines show the calculated pressure dependences, including the pressure effects on  $L_x$  and  $m_e^*$ , for several assumed pressure dependences of the band offset  $Q_{CB}$ ,  $dQ_{CB}/dP$  (1/kbar). (In the top curve the pressure dependence of the effective mass is neglected).

**Reference:**

1. U. Venkateswaran, M. Chandrasekhar, H.R. Chandrasekhar, B.A. Vojak, F.A. Chambers, and J.M. Meese, *Phys. Rev.* **B33**, 8416 (1986); D.J. Wolford, T.F. Kuech, J.A. Bradley, M.A. Gell, D. Ninno, and M. Jaros, *J. Vac. Sci. Technol.* **B4**, 1043 (1986).

**ANNUAL REPORT OF  
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

**a. Papers Submitted to Refereed Journals (and not yet published)**

J.H. Burnett, H.M. Cheong, W. Paul, E.S. Koteles, and B. Elman, "Investigation of  $\Gamma$ -X Mixing in GaAs/ $\text{Al}_x\text{Ga}_{1-x}\text{As}$  Coupled Double Quantum Wells Using Hydrostatic Pressure," submitted to *Physical Review B*.

H.M. Cheong, J.H. Burnett, W. Paul, P.M. Young, and J.F. Schetzina, "Pressure Dependence of Infrared Photoluminescence Spectra from HgTe/CdTe Superlattices," submitted to the 7th International Conference on Narrow Gap Semiconductors, Southampton, UK, 19-23 July 1992, to be published in *Semiconductor Science and Technology*.

J.H. Burnett, H.M. Cheong, W. Paul, P.F. Hopkins, and A.C. Gossard, "Pressure Dependence of the Harmonic Oscillator Levels of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  Parabolic Quantum Wells," abstract submitted to the Fifth International Conference on High Pressure Physics of Semiconductors, Kyoto, 1992.

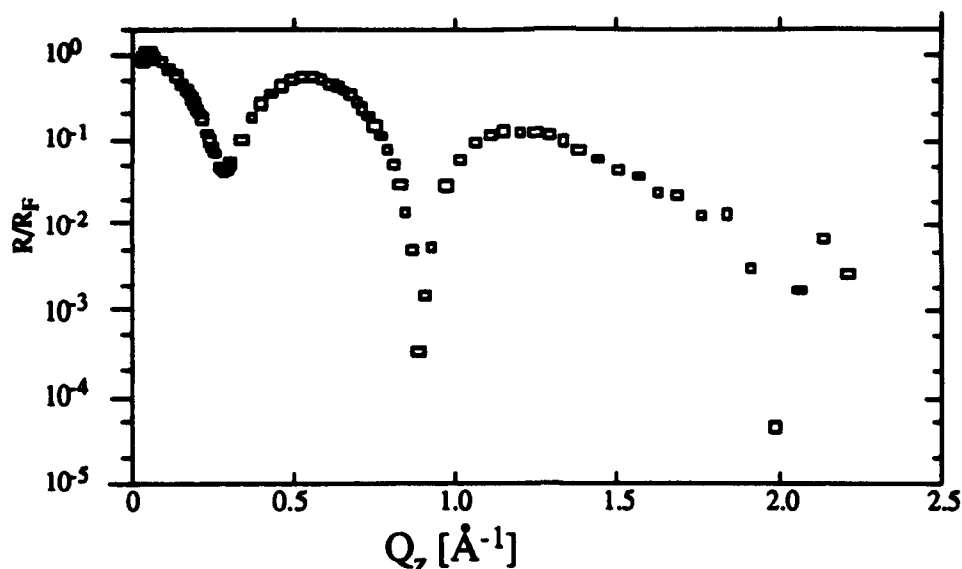
**j. Graduate Students and Postdoctorals Supported under the JSEP for the Year Ending July 31, 1992**

Dr. J.H. Burnett and Mr. H.M. Cheong.

**I.3 X-ray Surface Characterization.** I.M. Tidswell, T. Rabedeau, and P.S. Pershan, Grants N00014-89-J-1023, NSF DMR-89-20490, NSF DMR 91-13782; Research Unit 3.

The results on the X-ray scattering study of the  $\text{SiO}_2/\text{Si}(001)$  interface that was formed by dry oxidation of the  $\text{Si}(001)$  were described in the report for the previous period and the publications resulting from that work have now appeared in print [1, 2]. That project had been stimulated by published disagreement over whether or not the  $\text{SiO}_2/\text{Si}(001)$  interface consisted of an epitaxial layer of ordered oxide [3-8]. Our results resolved some of this controversy by demonstrating that for a room temperature oxidation process the epitaxially ordered fraction of  $\text{SiO}_2$  covers no more than  $\sim 8\%$  of the interface, the remaining being amorphous, and even this small fraction of epitaxially ordered  $\text{SiO}_2$  is unstable against either exposure to ambient air (i.e., wet  $\text{O}_2$ ) or 1 hour post-oxidation anneal at  $550^\circ\text{C}$ . We conjectured that the low initial fractional coverage and the instability against humidity or temperature might have been related to the inherent strain induced by the lattice mismatch between the  $\text{Si}(001)$  and the  $\text{SiO}_2$  [9-12], and we proposed studying the oxidation of Si layers that are epitaxially deposited on substrates made of alloys of  $\text{Si}_x\text{Ge}_{1-x}/\text{Ge}(001)$ . By varying the concentration over the range  $1 \geq x \geq 0$  tensile strains in the Si lattice can be varied from 0 to  $> 4\%$ . Since application of an external compressive stress is known to reduce the internal stress on the dimer, we expect that the dimer interfacial structure will be less stable when deposited on the  $\text{Si}_x\text{Ge}_{10x}/\text{Ge}$  substrate than on the Si [13].

Although sample preparation for this project was delayed some months as a result of necessary maintenance for the particular AT&T MBE machine that this program was designed around, the machine was recommissioned at the end of 1991 and a good  $\text{Ge}(001)$  surface was prepared and evaluated using the Harvard Rotating Anode. To form that sample a single crystal (miscut  $< 0.5^\circ$ ) was epitaxially coated



**Figure 1.3.** The ratio of the measured X-ray reflectivity,  $R(Q_z)$  for the Ge[001]/Si/SiO<sub>2</sub> described in the text, to the theoretical Fresnel reflectivity,  $R_F(Q_z)$  for a flat surface with the same average electron density as crystalline Ge. The minima at  $Q_z \cong 0.29 \text{ \AA}^{-1}$  and  $0.88 \text{ \AA}^{-1}$  correspond to destructive interference between reflections from the  $\cong 11 \text{ \AA}$  thick Si/SiO<sub>2</sub> layer (e.g.,  $Q_z d = \pi$  and  $3\pi$ ). Note that the interference minima at  $Q_z \cong 1.45 \text{ \AA}^{-1}$ ,  $Q_z d = 5\pi$ , corresponding to the anti-Bragg (002) point of Ge is missing as expected.

with approximately 2000 Å of Ge at 400°C, following which it was annealed at 500°C for 10 minutes; four monolayers of Si were then epitaxially deposited between 250–350°C. The sample was exposed to dry O<sub>2</sub> at room temperature for approximately 20 hours.

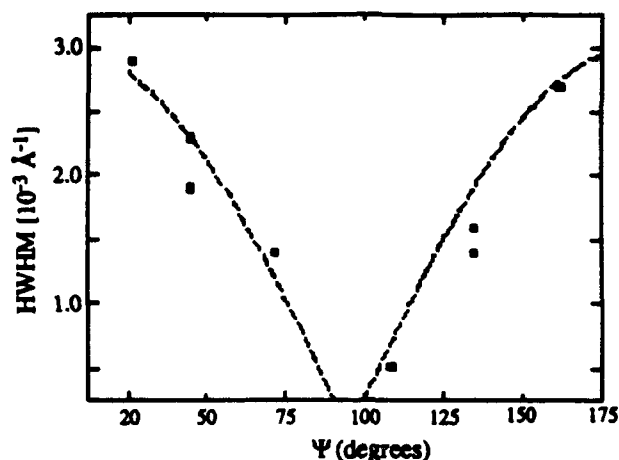
The results of specular reflectivity measurements that were made in March 1992 on beam line X20 at the National Synchrotron Light Source (NSLS) are shown in Figure 1.3.

A second beam allotment on X20a at NSLS was assigned to this project for the period from May 14th through May 31st. Since this report is being prepared on June 1 we present only the data with a minimum of analysis. We have used the splitting between four inequivalent (1,1,±1) and (1,3,±1) truncation rods near to the [001] plane to measure the angle of the miscut between the surface normal and the [001] axis of the same Ge/Si/SiO<sub>2</sub> sample that was studied in March; it is approximately 0.05° and

near to the  $[100]$  direction. In contrast to the  $\text{Si}[001]/\text{SiO}_2$  surface that we previously studied we do not observe long-range order in the surface steps [2]. Presumably this is because in the earlier experiment the miscut for the Si crystal was close to the  $[110]$  direction that is favored by surface steps on the  $[001]$  face of Si and Ge [14–19]. With the miscut pointing towards the  $[100]$  direction the surface steps are surely faceted with individual segments along the  $[1, \pm 1, 0]$  directions and long-range order is less likely.

We have measured eight different fractional order surface peaks and demonstrated that the anisotropy of the surface correlation lengths are significantly shorter along the miscut direction than in the perpendicular direction. Figure I.4 illustrates the raw data for the HWHM of transverse (e.g., rocking) scan through these eight fractional order peaks as a function of the angle between the direction of the scan and the  $[100]$  axis. The broken line was hastily drawn to illustrate the systematics of the data. It represents  $0.003 \times |\cos[\Psi - \phi]|$  where  $\Psi$  is the direction of the transverse scan through a surface peak, e.g., for a transverse scan parallel to the surface and through the  $(1/2, 3/2, .03)$  point, the angle  $\Psi \equiv \tan^{-1}(1/-3) = 108.43^\circ$ . The angle of the miscut away from the  $[100]$  direction was calculated from the observed splitting to be  $\phi \cong 5^\circ$ .

The  $Q_z$  dependence of the  $(1,1,Q_z)$  truncation rod and the  $(1/2,1/2,Q_z)$  fractional order rod have been measured. Interference oscillations on the  $(1,1,Q_z)$  rods and the absence of any structure on the  $(1/2,1/2,Q_z)$  suggest that the fractional order peaks, which we presume to be due to the  $1 \times 2$  dimer previously seen on the surface oxidized surface of  $\text{Si}(001)/\text{SiO}_2$  [20], are only one monolayer thick while the commensurate  $(1 \times 1)$  order of the epitaxial  $\text{SiO}_2$  may be four layers thick. Quantitative analysis will confirm some details of the initial interpretation of the raw data; there are a number of further experiments that will be necessary in order to obtain a firm picture of this surface.



**Figure 1.4.** Illustration of the dependence of the observed HWHM for transverse GID scans through eight different fractional order peaks. The direction that a transverse scan through a peak  $(h,k,0.033)$  makes with respect to the (100) direction is given by  $\Psi = \tan^{-1}(h/-k)$ . The broken line, which is simply a guide for the eye is given by  $0.003 \times |\cos[\Psi - \phi]|$  where  $\phi \cong 5^\circ$  is the angle between the projection of the miscut direction on the surface and the [001] direction.

The most compelling X-ray measurements that need to be made on the present sample include characterization of other fractional order rods. It is not proven that the surface domains are  $(1 \times 2)$  rather than  $(2 \times 2)$  [20]; however, on the basis of that assumption we would like to see if the two inequivalent  $(1 \times 2)$  domains are equally occupied. To that end, and also to get further information about the structure factor of the  $(1 \times 2)$  surface lattice, we will also measure scattering along the  $Q_z$  direction for other fractional order rods. We would also like to compare the specular reflection with the miscut oriented perpendicular to the plane of incidence with the data in Figure I.3 which was taken with the miscut in the plane of incidence. This will give information on the degree of microroughness within the individual terraces in the stepped surface. The most important measurement will be to tune the beam line to an energy near to the peak in the anomalous dispersion of the Ge scattering factor,  $\lambda \cong 1.13 \text{ \AA}$  in order to compare with scattering observed at  $\lambda = 1.41 \text{ \AA}$  that is currently being used. Since the near resonant energy will enhance the scattering amplitude of the Ge by nearly a factor of 10 relative to that of the Si and O this experiment would enable us to produce independent models for the Si and Ge surface distributions. We will

also explore possibilities of using other techniques, such as TEM, STM, SEXAFS, and photoelectron spectroscopy to obtain information that would complement our structural results.

At some point we will prepare Si layers on alloy substrates such as  $\text{Si}_x\text{Ge}_{1-x}$  and make comparable studies in order to systematically vary the effect of strain on the  $\text{SiO}_2$  surface layers.

### References:

1. T.A. Rabedeau, I.M. Tidswell, P.S. Pershan, J. Bevk and B.S. Freer, *Appl. Phys. Lett.* **59**, 706 (1991).
2. T.A. Rabedeau, I.M. Tidswell, P.S. Pershan, J. Bevk and B.S. Freer, *Appl. Phys. Lett.* **59**, 3422 (1991).
3. J.M. Gibson and M.Y. Lanzerotti, *Nature* **340**, 128 (1989).
4. P.H. Fuoss, L.J. Norton, S. Brennan and A. Fischer-Colbrie, *Phys. Rev. Lett.* **60**, 600 (1988).
5. A. Ourmazd, D.W. Taylor, J.A. Rentschler and J. Bevk, *Phys. Rev. Lett.* **59**, 213 (1987).
6. A. Ourmazd and J. Bevk, "The structure of the Si/ $\text{SiO}_2$  interface: A review" in *Materials Research Society Symposium Proceedings:  $\text{SiO}_2$  and Its Interfaces*, Vol. 105 (Materials Research Society, Pittsburgh, PA, 1988), edited by S.T. Pantelides and G. Luovsky, p. 1.
7. F.J. Himpsel, F.R. McFeely, A. Taleb-Ibrahimi, J.A. Yarmoff and G. Hollinger, *Phys. Rev.* **B38**, 6084 (1988).
8. G. Renaud, P.H. Fuoss, A. Ourmazd, J. Bevk, B.S. Freer and P.O. Hahn, *Appl. Phys. Lett.* **58**, 1044 (1991).
9. I. Ohdomari, H. Akatsu, Y. Yamakoshi and K. Kishimoto, *J. Appl. Phys.* **62**, 3751 (1987).
10. A. Fargeix and G. Ghibaudo, *J. Appl. Phys.* **54**, 7153 (1983).
11. A.M. Stoneham, C.R.M. Grovenor and A. Cerezo, *Phil. Mag.* **B55**, 201 (1987).
12. N.F. Mott, S. Rigo, F. Rochet and A.M. Stoneham, *Phil. Mag.* **B60**, 189 (1989).
13. F.K. Men, W.E. Packard, Y. Yamakoshi and K. Kishimoto, *Phys. Rev. Lett.* **61**, 2469 (1988).

14. R.M. Tromp and M.C. Reuter, *Phys. Rev. Lett.* **68**, 820 (1992).
15. J. Tersoff and E. Pehlke, *Phys. Rev. Lett.* **68**, 816 (1991).
16. E. Pehlke and J. Tersoff, *Phys. Rev. Lett.* **67**, 1290 (1991).
17. E. Pehlke and J. Tersoff, *Phys. Rev. Lett.* **67**, 465 (1991).
18. J.J. de Miguel, C.E. Aumann, R. Kariotis and M.G. Lagally, *Phys. Rev. Lett.* **67**, 2830 (1991).
19. X. Tong and P.A. Bennett, *Phys. Rev. Lett.* **67**, 101 (1991).
20. D.E. Jesson, S.J. Pennycook and J.-M. Baribeau, *Phys. Rev. Lett.* **66**, 750 (1991).  
A  $(2 \times 2)$  SiGe structure has been observed in  $\text{Se}_{0.5}\text{Ge}_{0.5}$  alloys; however, we think it unlikely that this structure could have formed in the present sample. Although a  $(2 \times 2)$  SiGe structure has been observed in  $\text{Se}_{0.5}\text{Ge}_{0.5}$  alloys; however, we think it unlikely that this structure could have formed in the present sample.

## ANNUAL REPORT OF PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

### b. Papers Submitted to Refereed Journals (and not yet published)

T.A. Rabedeau, I.M. Tidswell, P.S. Pershan, J. Bevk, and B.S. Freer, "X-ray Scattering Studies of the  $\text{SiO}_2/\text{Si}(001)$  Interfacial Structure," *Appl. Phys. Lett.* **59**, 706 (1991). (Partially supported by DE-AC02-76CH00016, NSF DMR-87-19217)

T.A. Rabedeau, I.M. Tidswell, P.S. Pershan, J. Bevk, and B.S. Freer, "X-ray Reflectivity Studies of  $\text{SiO}_2/\text{Si}(001)$ ," *Appl. Phys. Lett.* **59**, 3422 (1991). (Partially supported by DE-AC02-76CH00016, NSF DMR-87-19217)

### j. Graduate Students and Postdoctorals Supported under the JSEP for the Year Ending July 31, 1992

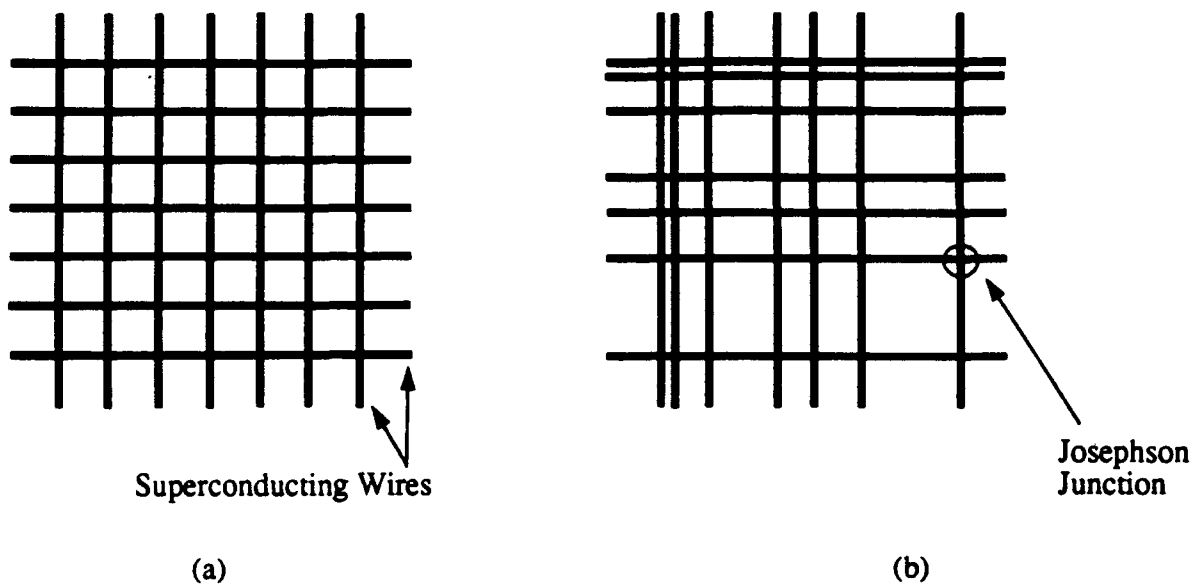
Dr. Ellen Hsu, Mr. Seth Kosowsky, and Dr. Tom Rabedeau

**I.4 Superconducting Josephson Junction Arrays.** M.S. Rzchowski, L.L. Sohn, T.S. Tighe, and M. Tinkham, Grants N00014-89-J-1023, N00014-89-J-1565, and DMR-89-12927; Research Unit 4.

After winding up the work on giant Shapiro steps stemming from coherent fluxon motion induced by rf-drive currents in conventional SNS arrays of various geometries, we have shifted our focus to a novel array geometry which results in *long-range* interactions. Rather than consisting of superconducting islands which are Josephson-coupled to nearest neighbors, these new arrays consist of two orthogonal sets of  $N$  parallel superconducting *wires* which are coupled by a Josephson junction at every point of crossing. (See Figure I.5.) As a result of this unique geometry, all the wires in the array are Josephson-coupled to each other as nearest- or next-nearest neighbors. Instead of being coupled to 4 or 6 neighbors, they are coupled to  $N$  ( $\sim 1000$ ) neighbors, and a mean-field description might be expected to be applicable. Indeed, this approach was used by Vinokur *et al.* [1], who first drew attention to the interesting properties of such arrays, particularly in the presence of a magnetic field and if the spacing of the wires was disordered.

Our approach to this system has combined theory and experiment. On the theory side, we worked out the phase transition of the system to a state showing long-range phase coherence [2]. We did this both by a mean-field approximation and by Monte Carlo simulations, for regular and disordered arrays, and both in and out of a magnetic field. Our work confirmed that, in zero-field, the phase transition to a phase-coherent state should occur at a temperature  $T_c$  which scales with  $N$ , the number of wires coupled as nearest-neighbors to any given wire. In the presence of a field,  $T_c$  is depressed by an amount depending on the field strength, and upon whether the arrays are ordered or disordered.

On the experimental side [3], we developed a technique to fabricate such arrays, typically with  $N = 1000$  parallel Nb thin-film wires in each set, with a  $2.5\ \mu\text{m}$  line width



**Figure 1.5.** Sections of an (a) ordered and (b) disordered array. The black lines are the superconducting wires. Each wire is coupled to every orthogonal wire by a Josephson junction.

and  $5\text{ }\mu\text{m}$  spacing, and with AlOx barrier tunnel junctions at each point of crossing. These individual junctions typically had normal state resistances  $r_n$  of  $\sim 670\text{ }\Omega$  and critical currents  $i_c$  of  $\sim 0.5\text{ }\mu\text{A}$ . When we measured the collective properties of the arrays, however, we found that they were far from those predicted by the idealized model. For example, the critical current between one wire and another was not  $Ni_c$  as would be expected naively for  $N$  ( $=1000$ ) junctions in parallel, but  $N_{\text{eff}}i_c$ , where  $N_{\text{eff}} \sim 20 \ll 1000$ . Similarly, the  $T_c$  at which long-range phase coherence sets in also acts as if an even smaller number  $N_{\text{eff}}$  of wires were relevant. We have traced these major discrepancies from standard theory to the fact that a phase-gradient is set up along the drive wire by the current itself, in addition to that caused by any externally applied field. This sets up a “soliton” structure in the current pattern, which limits  $N_{\text{eff}}$  to a number that scales with the square root of the ratio of the inductance of the wire in one unit cell to the Josephson inductance of a junction. We have developed a detailed model which accounts well for the reduction in the critical current of the array below the naive estimate, and accounts at least qualitatively for the other discrepancies. This work points the way to a second generation set of experiments, with improved samples

designed taking account of these inductive effects. It also points to the need for a more comprehensive theory of this novel and interesting system in the dynamic state above  $I_c$ , where surprising hysteretic and nonlinear effects are observed experimentally.

#### References:

1. V.M. Vinokur, L.B. Ioffe, A.I. Larkin, and M.V. Feigel'man, *Soviet Physics JETP* **66**, 198 (1987).
2. L.L. Sohn, M.S. Rzchowski, M.T. Tuominen, J.U. Free, and M. Tinkham, *Phys. Rev. B*, submitted.
3. L.L. Sohn, M.T. Tuominen, M.S. Rzchowski, J.U. Free, and M. Tinkham, *Phys. Rev. B*, submitted.

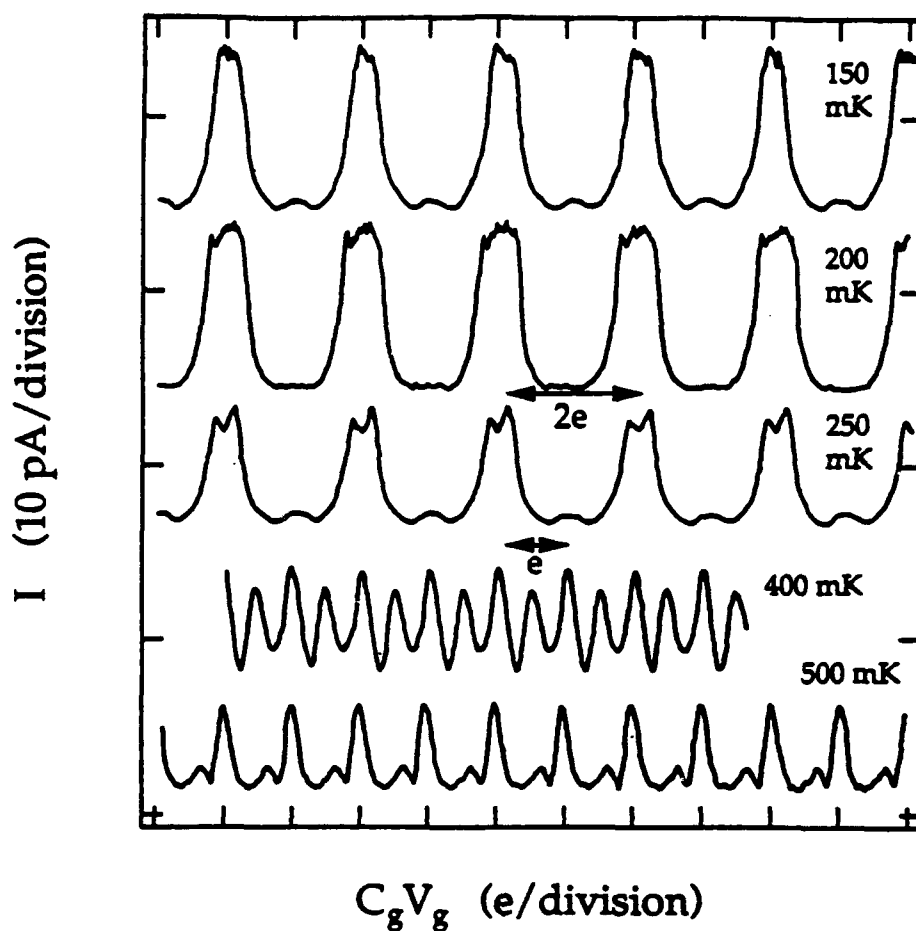
**I.5 Single-Electron Tunneling Devices** A. Hanna, M. Tuominen, J. Hergenrother, and M. Tinkham, Grants N00014-89-J-1023, N00014-89-J-1565, and DMR-89-12927; Research Unit 4.

These devices are based on the use of mesoscopic structures which are sufficiently small that their capacitance  $C$  is less than  $10^{-15}$  F, so that the charging energy  $e^2/2C$  of a single electron is the dominant energy in the problem. We are pursuing two approaches to this regime: one based on the STM, and the other based on thin film nanofabrication.

The first approach to succeed was the STM-based geometry. In this there is a gold grain of  $\sim 50\text{\AA}$  diameter, into which current tunnels from the STM tip, and then tunnels out to the Nb/NbOx substrate. With this device, capacitances as small as  $10^{-18}$  F are readily obtained. This is small enough that the device shows little thermal rounding of its I-V characteristics at 4K, and shows observable Coulomb blockade effects even at room temperature. Our first successes [1] with this technique of forming a "single-electron transistor" were reported in the previous Annual Report, confirming that a charge shift of only  $e/2$  is sufficient to take the device from zero to maximum conductance. Our major advance during the past year was to demonstrate

for the first time [2] the observability of elastic q-MQT, i.e., the so-called macroscopic quantum tunneling of charge by a coherent double tunneling process which leaves no excitation energy behind in the grain between the two tunnel links. This process yields a tiny linear conductance in the Coulomb blockade region,  $\sim 1000$  times smaller than outside of the Coulomb blockade, but observable at the pA level of sensitivity. Since the strength of this process depends inversely on the volume of the grain, the tiny grain used in this configuration is essential to the observability of this effect, which has never been seen in a fabricated thin film device.

In parallel with the STM work, we have been developing techniques for nanofabrication of thin-film realizations of the single-electron tunneling transistor concept. We use an Al-Al<sub>2</sub>O<sub>3</sub>-Al structure, with 600Å line width, yielding junctions with capacitance  $2 \times 10^{-16}$  F. This is low enough to allow operation at temperatures which can be reached *without* use of a dilution refrigerator, although we do use one to explore the limiting behavior at very low temperatures. Our major focus in this work is to emphasize the unique features which arise when the Al is in the superconducting state, in which there is a competition between the superconducting energy gap and the Coulomb charging energy gap. This causes the current through the device to show a complex periodic variation with the bias potential on the gate electrode. In all previous work this variation has shown an  $e$ -periodicity, repeating each time the gate voltage is changed sufficiently to pull another electron onto the island. However, in one particularly good sample, we have found [3] a  $2e$ -periodicity for all  $T \leq 300$  mK. The crossover in period is shown in Figure I.6. This  $2e$  period reflects the dominance of Cooper pairs in the superconducting state, but in less perfect samples single-electron tunneling events obscure its presence. We can account theoretically for our data by noting that, at low temperatures, the superconducting pairing energy favors states with an even number of electrons on the island. The cut-off at 300 mK reflects the fact that at this temperature, statistically speaking, a *single* quasiparticle is thermally



**Figure 1.6.** Dependence of device current on gate voltage at bias voltage of  $100\ \mu\text{V}$  and various temperatures. Other data not shown here show that the  $2e$ -periodicity vanishes near  $300\ \text{mK}$ .

excited above the gap in the *entire* island electrode. We believe this is the first time that an experimental distinction has been made between an odd and an even number of electrons on a fabricated metal structure.

#### References:

1. A.E. Hanna and M. Tinkham, *Phys. Rev. B* **44**, 5919 (1991).
2. A.E. Hanna, M.T. Tuominen, and M. Tinkham, *Phys. Rev. Lett.* **68**, 3228 (1992).
3. M.T. Tuominen, J.M. Hergenrother, T.S. Tighe, and M. Tinkham, *Phys. Rev. Lett.*, submitted.

## ANNUAL REPORT OF PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

### a. Papers Submitted to Refereed Journals (and not yet published)

L. Ji, M.S. Rzchowski, N. Anand, and M. Tinkham, "Magnetic-Field-Dependent Surface Resistance and 2-Level Critical State Model for Granular Superconductors," *Phys. Rev. B*.

L.L. Sohn, M.S. Rzchowski, J.U. Free, and M. Tinkham, "Phase Transitions in Josephson Junction Arrays With Long-Range Interaction," *Phys. Rev. B*.

L.L. Sohn, M.T. Tuominen, M.S. Rzchowski, J.U. Free, and M. Tinkham, "AC and DC Properties of Josephson-Junction Arrays With Long-Range Interaction," *Phys. Rev. B*.

M.T. Tuominen, J.M. Hergenrother, T.S. Tighe, and M. Tinkham, "2e-Periodicity in a Superconducting Single-Electron Tunneling Transistor," *Phys. Rev. Lett.*

### b. Papers Published in Refereed Journals

L.L. Sohn, M.S. Rzchowski, J.U. Free, S.P. Benz, M. Tinkham, and C.J. Lobb, "Absence of Fractional Giant Shapiro Steps in Diagonal Josephson Junction Arrays," *Phys. Rev. B* **44**, 925-928 (1991).

M.B.F. Cohn, M.S. Rzchowski, S.P. Benz, and C.J. Lobb, "Vortex-Defect Interactions in Josephson Junction Arrays," *Phys. Rev. B* **43**, 12823-12826 (1991).

T.S. Tighe, A.T. Johnson, and M. Tinkham, "Vortex Motion in Two-Dimensional Arrays of Small, Underdamped Josephson Junctions," *Phys. Rev. B* **44**, 10286-10290 (1991).

A.E. Hanna and M. Tinkham, "Variation of the Coulomb Staircase in a Two Junction System by Fractional Electron Charge" *Phys. Rev. B* **44**, 5919-5922 (1991).

L.L. Sohn, M.S. Rzchowski, J.U. Free, M. Tinkham, and C.J. Lobb, "Effect of Current Direction on the Dynamics of Josephson-Junction Arrays," *Phys. Rev. B* **45**, 3003-3012 (1992).

A.E. Hanna, M.T. Tuominen, and M. Tinkham, "Observation of Elastic Macroscopic Quantum Tunneling of the Charge Variable," *Phys. Rev. Lett.* **68**, 3228-3231 (1992).

**d. Books (and sections thereof) Published**

M. Tinkham, "Josephson Effect in Low-Capacitance Tunnel Junctions," Series of Invited Lectures at NATO ASI on *Single Charge Tunneling*, Les Houches, March 1991; chapter in *Single Charge Tunneling*, Grabert and Devoret, eds., Plenum, NY, 1992, pp. 139-166.

M. Tinkham, "Conference Summary," Los Alamos Symposium 1991, published in *Phenomenology and Application of High-Temperature Superconductors*, Addison-Wesley, 1992, pp. 499-514.

M. Tinkham, "Josephson Effects in Weak Links," article in *Concise Encyclopedia of Magnetic and Superconducting Materials*, edited by J. Evetts, Pergamon Press, 1992, pp. 203-207.

**h. Contributed Presentations at Topical or Scientific/Technical Society Conferences**

M.S. Rzchowski, L.L. Sohn, and M. Tinkham, "Josephson Junction Arrays with Long-Range Interaction," March 1992 Meeting of the American Physical Society.

L.L. Sohn, M.S. Rzchowski, M.T. Tuominen, J.U. Free, and M. Tinkham, "Properties of Josephson Junction Arrays with Long-Range Interaction," March 1992 Meeting of the American Physical Society.

T.S. Tighe, M.T. Tuominen, J.M. Hergenrother, and M. Tinkham, "Charging Effect Measurements of 2D Arrays of Ultrasmall Josephson Junctions," March 1992 Meeting of the American Physical Society.

A.E. Hanna and M. Tinkham, "Single Electron Dynamics in a Two Junction System," March 1992 Meeting of the American Physical Society.

**j. Graduate Students and Postdoctorals Supported Under the JSEP for the Year Ending July 31, 1992**

Dr. M.S. Rzchowski and Mr. N. Anand.

**Note:** Five other students share JSEP facilities, but have no JSEP salary. Also, all listed publications acknowledge shared support from the other grants enumerated at the beginning of the text.

**I.6 Neural Networks.** F.R. Waugh, R. Seshadri, C. Marcus, and R.M. Westervelt, Grant N00014-89-J-1023; Research Unit 5.

For a number of years we have focussed our efforts in the Joint Services Electronics Program on electronic neural networks, and on the dynamics of magnetic domain patterns in garnet films. This research has been quite successful as described below and in previous annual reports. Beginning this year, we intend to shift our JSEP-supported efforts toward the physics of electronic nanostructures. With recent improvements in electron beam lithography, we now have state-of-the-art facilities in the McKay laboratory for the production and characterization of nanostructures. Professor Westervelt's group uses these facilities to make and study GaAs/AlGaAs nanostructures in collaboration with Prof. A.C. Gossard at the University of California, Santa Barbara, while Professor Tinkham's group is expert in the fabrication and study of metallic and superconducting nanostructures. The presence of both groups in the McKay laboratory offers excellent opportunities for new collaborative work, because many of the physical issues are similar. For example, as described below we are currently developing hybrid semiconductor/superconductor samples in which a Josephson junction is used to illuminate a semiconducting quantum point contact with submillimeter wavelength radiation. If successful, this technique will permit spectroscopy of single nanostructures in this difficult frequency range.

**A. Competitive Neural Networks for Vision**

In the past we have developed general techniques to stabilize fully interconnected electronic neural networks by clocking, and have conducted a systematic study of their dynamics and stability. In the past year we have applied these techniques by developing a new type of neural net architecture for problems in vision. The general approach is similar to the neocognitron developed by Fukushima. The network is subdivided into identical cells which are programmed to recognize elementary image features. These features are then combined via inter-cell connections into more complex objects. In

competitive networks, we represent each elementary feature by a single neuron in a cell and implement a variation of the winner-take-all circuit by requiring that the summed output of all neurons within a given cell is a constant. This architecture requires many fewer interconnections than our previous approach in which each cell was a fully interconnected network of pixels, and is well suited to implementation in hardware. Assembly of the elementary features favored by individual cells into a single recognized object is done via inter-cell connections which can either be all-to-all or limited to nearest neighbors. We have conducted a systematic analytical study of the stability of clocked neural nets of this type, and demonstrated the concept in numerical experiments [1].

## **B. Statistical Mechanics of Magnetic Bubble Arrays**

In the past year we have completed a study of the dynamics and statistical mechanics of magnetic bubble arrays in thin garnet films [2-5]. A magnetic bubble array is an experimentally-accessible example of a two-dimensional fluid similar in some respects to vortex arrays in type-II superconductors. We use observations of the dynamics of bubble arrays to test theories of vortex dynamics in collaboration with Professors David Nelson and Daniel Fisher at Harvard. We have shown that bubble arrays undergo a hexatic-to-liquid melting transition [2], and have systematically studied their statistical mechanics [3-4]. Most recently we have studied shear flow past a planar interface, in order to test the predictions of theories of flux pinning in high  $T_c$  superconductors [5]. Flux flow is important in high  $T_c$  materials, because it produces power dissipation and destroys the advantage of superconductivity. This work was supported primarily by a separate grant from the Office of Naval Research, and we will shift the support of future work in this area entirely to the ONR.

## **C. Semiconductor Nanostructures**

In the past year we have developed and used new facilities for the production

and characterization of semiconductor nanostructures, with partial JSEP support. Electron beam lithography has been used to make submicron quantum boxes with quantum point contacts which we have used to study chaotic scattering of electrons [6]. We find that chaotic scattering of electrons from the walls of a quantum box produces features in the low temperature magnetoresistance analogous to weak localization and universal conductance fluctuations. The difference is that scattering in our structures is primarily from the walls of the box and depends on its shape, while localization and universal conductance fluctuations are caused random impurity scattering. Shape-dependent fluctuation phenomena are a fundamental source of noise disorder for any quantum nanostructure in which electrons propagate coherently.

We have also used our lithography facilities to study the subband structure of electrons in wide parabolic quantum wells via capacitance-voltage (CV) measurements. The Fermi energy of electrons in quantum structures introduces a quantum term to the total capacitance, because the measured voltage between an electron gas and a gate is actually the total change in electrochemical potential. Rimberg *et al.* [7] demonstrate that CV-profiling measurements on parabolic wells with in-plane magnetic fields show features which can be unambiguously associated with Fermi level changes due to subband depopulations, in addition to profiling the charge density of the electron layer. In the future we plan to extend the sensitivity of this technique with custom made on chip transistors to do quantum CV profiling on single nanostructures, as recently demonstrated by Ashoori and coworkers.

Nanostructure electronic devices which operate via quantum mechanical principles show promise for applications in computing and signal processing. Although their practical use lies in the future, we can study the physics of operation of nanostructure devices now in order to determine which approaches might work and to understand their fundamental limitations. Because the temperature of operation scales inversely with device size, what we learn from measurements of present nanostructures with

size  $> 50$  nm at very low temperatures will apply to smaller structures in the future which operate at more accessible temperatures. We have excellent facilities for nanostructure research at Harvard, and opportunities for novel collaborative efforts between Prof. Tinkham's group (superconducting nanostructures), and Prof. Westervelt's (semiconducting nanostructures).

We propose to shift our efforts toward issues associated with the device physics of semiconductor nanostructures and superconductor/semiconductor hybrid structures. Two specific projects we intend to pursue are the development of custom-made cryogenic field-effect transistors for *in situ* measurements of single nanostructures, and the development of a Josephson junction oscillator for the irradiation of semiconductor nanostructures at submillimeter wavelengths.

#### **D. Cryogenic Field Effect Transistors**

Ashoori and coworkers have recently demonstrated the use of a GaAs heterostructure FET to make capacitive measurements of a single quantum dot. The FET is mounted adjacent to the dot sample and both are cooled to low temperatures. This configuration is naturally suited to charge-coupled measurements of nanostructures, because the input resistance is very high and the input capacitance is very low due to the small size of the gate and the short leads. We plan to extend these techniques by constructing matched FET pairs using the two-dimensional electron gas (2DEG) in GaAs/AlGaAs heterostructures. We currently fabricate gated Hall bar structures routinely for quantum Hall effect measurements, using either optical or electron-beam lithography. A differential FET pair can be constructed from two matched, gated 2DEG channels, whose input capacitance can be made very small by reducing the size of the transistors. The difference in charge on the two gates can be measured with high accuracy via the difference in channel resistances in a bridge circuit. The transistor pair can be fabricated on the same chip as the nanostructure sample to achieve extremely low input capacitance, or on a separate chip for measurements in

a magnetic field so that the 2DEG channel can be oriented parallel to the field lines. The extreme sensitivity possible with such devices should permit us to characterize single nanostructures in a wide variety of experiments. We do not expect difficulty in producing cryogenic circuits, because the yield on our lithography process for single devices is currently quite high.

#### **E. Josephson Junction/GaAs Heterostructure Hybrids**

Many quantum transitions of interest for semiconductor heterostructures and nanostructures lie in the submillimeter wave region of the spectrum. Spectroscopy on nanostructures is difficult, because the source and spectrometer are typically located outside the sample Dewar. Channeling submillimeter wave radiation to and from the sample poses special problems, especially for dilution refrigerator temperatures. Furthermore, arrays are usually required, because single nanostructures typically do not provide a detectable signal. These difficulties can be avoided by constructing a superconductor/semiconductor hybrid sample in which a Josephson junction is used as a tunable source of submillimeter radiation. By placing the nanostructure in the near field of the oscillating junction, the oscillating electric field pattern can be controlled, and unwanted radiation into the far-field can be largely avoided, so that all leads to the sample carry only dc signals. Hybrid devices such as these are naturally suited to the measurement of single nanostructures at dilution refrigerator temperatures. In collaboration with Prof. Tinkham's group, we have already begun fabricating test structures in which a Nb Josephson Junction is located adjacent to a quantum point contact in a GaAs two-dimensional electron gas. We are presently working to improve junction characteristics, and expect results in the near future. In these first experiments we intend to use the point contact as a threshold detector for submillimeter wave photons to demonstrate the viability of the technique. If successful, we will be able to do spectroscopy on single quantum point contacts and other structures.

## References:

1. F.R. Waugh, and R.M. Westervelt, "Dynamics of Analog Neural Networks with Local Competition," *Phys. Rev. A* (submitted).
2. R. Seshadri and R.M. Westervelt, "Hexatic-to-liquid Melting Transition in Two-dimensional Magnetic-bubble Lattices," *Phys. Rev. Lett.* **66**, 2774 (1991).
3. R. Seshadri and R.M. Westervelt, "Statistical Mechanics of Magnetic Bubble Arrays, Part 1: Topology and Thermalization," *Phys. Rev. A* (to appear).
4. R. Seshadri and R.M. Westervelt, "Statistical Mechanics of Magnetic Bubble Arrays, Part 2: Observations of Two-Dimensional Melting," *Phys. Rev. A* (to appear).
5. R. Seshadri and R.M. Westervelt, "Forced Flow of Two-Dimensional Magnetic Bubble Arrays," *Phys. Rev. Lett.* (to be submitted).
6. C.M. Marcus, A.J. Rimberg, R.M. Westervelt, P.F. Hopkins, and A.C. Gossard, "Conductance Fluctuations and Chaotic Scattering in Ballistic Microstructures," *Phys. Rev. Lett.* (to appear).
7. A.J. Rimberg, S. Yang, J. Dempsey, J.H. Baskey, R.M. Westervelt, M. Sundaram, and A.C. Gossard, "Capacitive Depletion of the Subband Structure in the Electron Gas in a Wide Parabolic Quantum Well," *Appl. Phys. Lett.* (submitted).

## ANNUAL REPORT OF

### PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

#### a. Papers Submitted to Refereed Journals (and not yet published)

R. Seshadri and R.M. Westervelt, "Two-Dimensional Melting of Hexatic Magnetic Bubble Arrays," in *Proc. Int. Conf. Two-Dimensional Physics*, Neuchatel, 1991. (Partially supported by N00014-89-J-1592)

R. Seshadri and R.M. Westervelt, "Statistical Mechanics of Magnetic Bubble Arrays, Part 1: Topology and Thermalization," *Phys. Rev. A*. (Partially supported by N00014-89-J-1592)

R. Seshadri and R.M. Westervelt, "Statistical Mechanics of Magnetic Bubble Arrays, Part 2: Observations of Two-Dimensional Melting," *Phys. Rev. A*. (Partially supported by N00014-89-J-1592)

R. Seshadri and R.M. Westervelt, "Two-Dimensional Melting of Magnetic Bubble Arrays: A Continuous Hexatic to Liquid Transition," *Proc. Fall Meeting of the MRS*, Boston 1991. (Partially supported by N00014-89-J-1592)

A.J. Rimberg, S. Yang, J. Dempsey, J.H. Baskey, R.M. Westervelt, M. Sundaram, and A.C. Gossard, "Capacitive Depletion of the Subband Structure in the Electron Gas in a Wide Parabolic Quantum Well," *Appl. Phys. Lett.* (Partially supported by N00014-89-J-1592)

R. Seshadri and R.M. Westervelt, "Forced Flow of Two-Dimensional Magnetic Bubble Arrays," *Phys. Rev. Lett.* (Partially supported by N00014-89-J-1592)

F.R. Waugh and R.M. Westervelt, "Dynamics of Analog Neural Networks with Local Competition," *Phys. Rev. A*. (Partially supported by DARPA AFOSR-89-0506)

C.M. Marcus, A.J. Rimberg, R.M. Westervelt, P.F. Hopkins, and A.C. Gossard, "Conductance Fluctuations and Chaotic Scattering in Ballistic Microstructures," *Phys. Rev. Lett.* (Partially supported by NSF DMR-88-17309 and DARPA AFOSR-89-0506)

#### b. Papers Published in Refereed Journals

C.M. Marcus, F.R. Waugh, and R.M. Westervelt, "Connection Topology and Dynamics in Lateral Inhibition Networks," in *Advances in Neural Information Processing Systems 3* (Morgan Kaufman, San Mateo, 1991), p. 98. (Partially supported by N00014-89-J-1592 and AFOSR-89-0506)

C.M. Marcus, F.R. Waugh, and R.M. Westervelt, "Nonlinear Dynamics and Stability of Analog Neural Networks," in *Nonlinear Science: The Next Decade*, Proc. 10th Annual Int. Conf. of the Center for Nonlinear Studies, Los Alamos, May 1990, D. Campbell, R. Ecke, and J.M. Hyman, eds. (North-Holland, Amsterdam, 1991), p. 234. (Partially supported by N00014-89-J-1592)

**c. Books (and sections thereof) Submitted for Publication**

F.R. Waugh, C.M. Marcus, and R.M. Westervelt, "Nonlinear Dynamics of Analog Associative Memories," in *Neural Associative Memories*, ed. M. Hassoun (Oxford University Press, Oxford, 1992). (Partially supported by DARPA AFOSR-89-0506)

**g. Invited Presentations at Topical, or Scientific/Technical Society Conferences**

R.M. Westervelt, "Avalanches in Magnetic Domain Patterns," Santa Fe Institute, Workshop on Self-Organized Criticality, September 1991.

R.M. Westervelt, "Space-Charge Dynamics in Ultrapure Ge," 1st Experimental Chaos Conference, Arlington, Virginia, October 1991. (Partially supported by N00014-89-J-1592)

R.M. Westervelt, "Two Dimensional Neural Networks for Vision," Neural Networks for Computing, Snowbird, Utah, April 1992.

R.M. Westervelt, "Forced Flow of Magnetic Bubble Arrays," 12th Annual CNLS Conference Nonlinearity and Materials Modeling: Simulations, Interpretation and Science," May 1992. (Partially supported by N00014-89-J-1592)

R.M. Westervelt, "Chaotic Scattering of Electrons in Quantum Dots," Joint Soviet-American Conference on Chaos, Kiev, Ukraine, July 1992. (Partially supported by N00014-89-J-1592)

R.M. Westervelt, "Forced Flow of Magnetic Bubble Arrays," Workshop on Spatially Extended Nonequilibrium Systems, Institute for Theoretical Physics, University of California, Santa Barbara, July 1992. (Partially supported by N00014-89-J-1592)

C.M. Marcus, "Experimental Investigations of Chaotic Scattering in Semiconductor Quantum Dots," CHAOS IV, Kiev, Ukraine, July 1992.

**h. Contributed Presentations at Topical, or Scientific/Technical Society Conferences**

C.M. Marcus, Meeting of the American Physical Society, Indianapolis, Indiana,

March 1992.

R. Seshadri, Meeting of the American Physical Society, Indianapolis, Indiana, March 1992.

R. Seshadri, International Conference on Statistical Physics, STATPHYS 18, Berlin, Germany, August 1992.

F. Waugh, International Conference on Statistical Physics, STATPHYS 18, Berlin, Germany, August 1992.

**i. Honors/Awards/Prizes**

R.M. Westervelt, Steering Committee, 4th Soviet-American Chaos Conference, 1992.

R.M. Westervelt, Naval Studies Board Review Panel, Naval Research Laboratory, 1992.

R.M. Westervelt, Nonlinear Dynamics Program Panel, National Science Foundation, 1991.

R.M. Westervelt, Member of JASON.

**j. Graduate Students and Postdoctorals Supported under the JSEP for the Year Ending July 31, 1992**

Dr. Charles Marcus, Mr. Fred Waugh and Ms. Raj Seshadri

## **I.7 Structural and Dynamical Studies of Semiconductor Interfaces and Surfaces.** J.A. Golovchenko, Grant N00014-89-J-1023; Research Unit 6.

We have completed the structural studies of lead overlayers on silicon and germanium surfaces with JSEP support. We chose these two systems because metal-semiconductor surfaces have been of great interest in science as well as in technological applications for decades. Furthermore, they both show reversible two-dimensional melting transitions which merit further study. Recently it was found on several systems (such as lead on silicon and nickel on silicon) that the Schottky barrier height depends strongly on the interface structure upon which the metal overlayer is deposited. Our studies of lead on silicon, mainly using a home-made tunneling microscope, have successfully resolved the controversy regarding the atomic structures and the number of different phases.

Recently we extended our study to dynamical processes on semiconductor surfaces. Since its invention, tunneling microscopy has mainly been used to image surface structures at atomic resolution. However, its use in the study of dynamics is rare. The study of atomic scale motions is of fundamental importance in the understanding of dynamical phenomena on surfaces, such as diffusion, phase transitions, and epitaxial growth. Therefore, our tunneling microscope was adapted to operate at temperatures above 25°C. This enables us to observe in detail motion of surface atoms. We found that a small number of lead atoms on the Ge(111) surface can catalyze atomic motions and thus allow their observation near room temperature. Our initial study of this system showed that the individual interchanges of lead and germanium atoms within the reconstructed Ge(111)-c(2 × 8) surface can be identified and that the interchange process is thermally activated and obeys the Arrhenius relation. Its activation energy and diffusion constant were determined by a plot of interchange rate vs. 1/T. We also found that this diffusion process occurs mainly along the adatom row direction of the c(2 × 8) reconstructed surface and that about half of the interchanges are "long

jumps" (movements of more than one atomic spacing). We believe this is the first direct observation of individual diffusion process and long jumps. A paper entitled "Direct Measurement of Diffusion by Hot Tunneling Microscopy: Activation Energy, Anisotropy, and Long Jumps" was published in March 1992 in *Physical Review Letters*.

Our further study of atomic motions for lead on the Ge(111) surface showed the formation and annihilation of metastable structural surface excitations. One of these excitations is associated with large numbers of germanium adatoms shifting positions along the adatom row like beads on an abacus. This effect provides a new mechanism for understanding the transport of atoms on a semiconductor surface. Also, it can account for the previously observed anisotropic diffusion and provides clues for the phase transition of pure Ge(111)-c( $2 \times 8$ ) to  $1 \times 1$  phase, which is still not well understood. We believe our observation of atomic motions will stimulate further theoretical calculations which may enhance the fundamental understanding of dynamical processes. A manuscript entitled "Observation of Metastable Structural Surface Excitations and Concerted Adatom Motions: Pb/Ge(111)" was submitted recently to *Science* magazine. A full report of our observations of atomic motions on this surface is in preparation.

A second tunneling microscope has been constructed in our laboratory. Clear images of Si(111)- $7 \times 7$  have been obtained at room temperature; however, minor modifications of the microscope and of the control electronics and software are still needed. This STM is also designed so that samples may be held at elevated temperature during tunneling, to facilitate additional studies of diffusion and growth kinetics. It will be used to continue our studies of diffusion on semiconductor surfaces and to study the growth of Ge on Si(111).

We have initiated studies of the structural and electronic properties of hydrogen- and halogen-terminated silicon (111) surfaces. It is known that atomically flat and electronically passivated hydrogen-terminated silicon (111) surfaces can be obtained

easily from chemical etching of a silicon wafer in buffered hydrofluoride solution. Each surface silicon atom is bound by one hydrogen atom, which saturates the surface dangling bond and passivates the surface. On the other hand, a reliable procedure to produce ideal halogen-terminated silicon surfaces is still to be found. To determine the surface quality of trial samples of halogen-terminated silicon surfaces, an X-ray standing wave setup has been completed and is being used to measure the position of bromine atoms chemisorbed on silicon (111) surfaces. Preliminary experimental results are consistent with the picture that one bromine atom is bound to one surface silicon atom. The measured distance between bromine atoms and bulk silicon (111) plane is 2.57 Å.

The mechanism of surface passivation and the formation of Schottky barriers are two important subjects in solid state electronics. We will extend our study of hydrogen- and halogen-terminated silicon surfaces to these two subjects and look for correlations between the structural and electronic properties of the surfaces. Stimulated by the realization of organic electroluminescent devices, we are looking into the possibility of binding dye molecules on silicon surfaces and making light-emitting devices out of them.

**ANNUAL REPORT OF  
PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

**a. Papers Submitted to Refereed Journals (and not yet published)**

I.-S. Hwang and J.A. Golovchenko, "Observation of Metastable Structural Surface Excitations and Concerted Adatom Motions: Pb/Ge(111)," *Science*.

**b. Papers Published in Refereed Journals**

E. Ganz, F. Xiong, I.-S. Hwang, and J.A. Golovchenko, "Submonolayer Phases of Pb on Si(111)," *Phys. Rev. B* **43**, 7316 (1991).

E. Ganz, I.-S. Hwang, F. Xiong, S.K. Theiss, and J.A. Golovchenko, "Growth and Morphology of Pb on Si(111)," *Surface Science* **257**, 259 (1991).

E. Ganz, S.K. Theiss, I.-S. Hwang, and J.A. Golovchenko, "Direct Measurement of Diffusion by Hot Tunneling Microscopy: Activation Energy, Anisotropy, and Long Jumps," *Phys. Rev. Lett.* **68**, 1567 (1992).

**g. Invited Presentations at Topical, or Scientific/Technical Society Conferences**

J.A. Golovchenko, "Metastable Structural Surface Excitations and Correlated Atomic Motion: A STM Study of the Mechanism of Surface Diffusion within a Semiconductor Surface," March 1992 Meeting of the American Physical Society.

**h. Contributed Presentations at Topical, or Scientific/Technical Society Conferences**

E. Ganz, F. Xiong, I.-S. Hwang, and J.A. Golovchenko, "Growth and Morphology of Pb on Si(111)  $7 \times 7$ ," Abstract for the 18th Annual Conf. on the *Physics and Chemistry of Semiconductor Interfaces*, Long Beach, California (1991).

**j. Graduate Students and Postdoctorals Supported under the JSEP for the Year Ending July 31, 1992**

Ms. Silva K. Theiss and Mr. Ing-Shouh Hwang



## II. QUANTUM ELECTRONICS

### Personnel

Prof. E. Mazur  
Dr. W. Mieher  
Mr. A. Feder  
Mr. J. Goldman  
Mr. S. Deliwala

Ms. K.Y. Lee  
Mr. C.Z. Lü  
Mr. E. Glezer  
Mr. Y. Siegal  
Mr. J.K. Wang

#### **II.1 Femtosecond Nonlinear Optical Interactions** E. Mazur, E. Glezer, Y. Siegal, and J.K. Wang, Grants N00014-89-J-1023 and NSF DMR-8858075; Research Unit 7.

In this past year we have taken extensive measurements of the response of GaAs to excitation with high-energy, 150-fs laser pulses. When excited above a threshold fluence of  $100 \text{ mJ/cm}^2$ , the electronic system in the material undergoes an ultrafast transformation to a disordered, metallic phase. The disordering is evidenced by the vanishing of the reflection second harmonic signal of a probe pulse with a 100-fs decay time while a sharp rise in linear reflectivity indicates the metallic character of the disordered phase. These results suggest that lattice disordering can be driven directly by the breaking of bonds through laser excitation of valence electrons to the conduction band and that this disordering can occur while the lattice is still cold.

In addition to the disordering measurements, we have obtained preliminary results on ultrahigh density carrier recombination below the disordering threshold using a highly sensitive probe of the index of refraction involving reflection second harmonic generation. Little is known about the behavior of GaAs in the high carrier density regime, and our results show an Auger carrier recombination time that is significantly faster than that predicted by theory. At carrier densities near  $10^{22}/\text{cm}^3$ , the measured recombination time is about 500 fs instead of the 10 ps value predicted by a static

screening model.

We recently completed rebuilding the laser amplifier with a novel, flexible design involving continuum generation in a single-mode optical fiber followed by amplification in prism dye cells. This design allows us to have two high-energy, independently tunable, synchronized beams of 60-fs laser pulses with excellent spatial profile. With this added flexibility we are now in a position to embark on a vigorous set of experiments designed to fully explore ultrafast laser-induced disordering as well as ultrahigh density carrier dynamics in semiconductors.

(i) *Studies of carrier dynamics at very high densities.* Using our sensitive reflection second harmonic probe of the index of refraction, we plan to examine more closely the behavior of carriers in crystalline GaAs at conduction electron densities greater than  $10^{21}$ . We can easily achieve these carrier densities with our femtosecond laser pulses because the laser energy is deposited on such a short time scale. Very little information exists on this regime of carrier dynamics, yet it is becoming more and more important to understand the physics at high carrier densities because this is precisely the situation in many new high technology devices. For example, because of the gain limiting effects of recombination, information on high carrier density Auger recombination times will be crucial in the rapidly developing field of semiconductor diode lasers.

(ii) *Temperature dependence of semiconductor disordering.* Since the electronically-induced disordering occurs before significant energy is transferred from the hot electrons to the lattice, the temperature of the lattice upon disordering is probably not much higher than room temperature. The average thermal velocity of the ions at room temperature is fast enough to lead to a metallic, disordered lattice in a few hundred femtoseconds if the bonds that hold the ions in place are suddenly removed. If this bond-breaking picture is accurate, then the measured disordering time should depend on the average thermal velocity of the ions upon excitation with

the laser pulse. We plan to build a cryogenic system that will allow us to cool the sample down to below 20°K. This will allow us to study the effects of slower initial ion velocities on the disordering time.

(iii) *Ellipsometry of Disordered Semiconductors.* Although we know that the short-lived phase of GaAs resulting from electronically-induced disordering is metallic in character, many more details remain to be learned about its nature. The dielectric constant at 620 nm which we extracted from our data does not match with theoretical simulations for the dielectric constant of equilibrium liquid GaAs, suggesting that femtosecond laser-induced disordering may result in a state unattainable through other means. By mapping out the index of refraction of disordered semiconductors using pump-probe ellipsometry, we can obtain a fairly detailed picture of these novel materials. Our new, tunable, laser amplifier gives us the ability to study the wavelength dependence of the index of refraction.

**II.2 Interactions with Ultrashort Laser Pulses.** E. Mazur, C.Z. Lü, S. Deliwala, and J. Goldman, Grants N00014-89-J-1023 and ARO DAAL03-88-K-0114; Research Unit 8.

In this research unit we made significant progress this year towards our goal of developing an experimental apparatus for femtosecond laser studies of molecular surface processes in ultrahigh vacuum (UHV). We completed renovation of our clean air lab facility, constructed a femtosecond Ti:Sapphire laser oscillator, designed a high-power high-repetition-rate laser amplifier, and designed and purchased a UHV surface science chamber.

The self-mode-locked Ti:Sapphire laser oscillator is currently operational and generates pulses of 80-fs duration. We chose Ti:Sapphire because of its great versatility as a short pulse source, being tunable with a single set of optics from 700–900 nm. The laser has excellent mechanical stability. A HITCI saturable absorber jet in the cavity stabilizes the self-mode locking process and provides long term pulse-train stability

required for our high-repetition rate multi-shot averaging techniques. A surprising advantage of the Ti:Sapphire oscillator is that it can produce very high average powers. Using a 20% output coupler, we obtain several watts of mode-locked infrared output for 10-15 W of argon laser pump power. This means that we can obtain tens of nJ per laser pulse, which is sufficient for continuum generation or second harmonic probing of surfaces without further amplification. These high pulse energies also eliminate the need for multiple stages of amplification; with a simple six-pass amplifier design we will be able to obtain about 1-10  $\mu$ J per pulse, and additional linear amplifier stages will allow us to produce energies in the 100  $\mu$ J range if we desire such pulses for disordering, desorption or reaction studies. Currently we are designing the amplifier section of the laser. Until funds can be obtained for a high repetition rate ( $\geq 1$  kHz) pump laser, we plan to use our existing 10-Hz Nd:YAG laser in a linear amplifier design. This will allow us to obtain preliminary data; on the long-term a high-repetition rate laser with a regenerative amplifier would allow us to increase the signal-to-noise ratio by several orders of magnitude.

Our proposed laser surface studies in UHV require a mechanically stable, compact chamber with short optical path length access to the sample over a wide range of angles. To this end we designed a two level chamber, with a vertically mounted VG manipulator which allows precision sample positioning in the upper or lower chambers. The lower level is a small six inch cube with windows on four sides, allowing positioning of lenses or other optical components outside the chamber only two inches away from the sample; with the sample in this position we can achieve a continuous 45 degree field of view which makes the alignment of several beams in a phase matched geometry much more practical. Backing the sample up to four inches from the windows allows grazing incidence geometries as well. The upper chamber level is equipped with standard surface preparation tools, a load lock, and characterization probes including mass spectrometry and LEED/Auger spectroscopy. The manipulator is designed to

allow rapid sample cooling to  $1N_2$  temperatures (down to 100 K) which is required for preparation of oxygenated metal surfaces.

The most immediate goal for this apparatus is to time-resolve a two-species laser-induced surface chemical process. In particular we are interested in the properties of metal catalytic surfaces with monolayer adsorbed coverages of gaseous molecules such as oxygen. We hope to test several nonlinear optical techniques for their effectiveness in characterizing these surfaces as they undergo molecular steps of reaction including vibrational and electronic excitation and relaxation, dissociation and desorption, and recombination into new species. Such studies offer enormous potential for furthering the understanding of these fundamental molecular processes, and for the possibility of laser-driven final-state-specific laser chemistry and materials processing. Experiments leading up to these goals will include laser-induced dissociation of  $O_2$  and detection of OH from a laser excited  $O_2/H_2$  coadsorbate surface. In addition to the surface reaction work, we plan to investigate the effect of laser-excited adsorbates on the electrical properties of semiconductor and metal surfaces — a study that may have significant import for device physics applications.

## ANNUAL REPORT OF

### PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

#### a. Papers Submitted to Refereed Journals (and not yet published)

J.-K. Wang, Y. Siegal, C. Lü, and E. Mazur, "Generation of Synchronized, Tunable, Femtosecond Laser Pulses with Nearly Perfect Gaussian Spatial Profile," *Opt. Comm.*

K.-H. Chen, C.-Z. Lü, J. Goldman, S. Deliwala, and E. Mazur, "Coherent Anti-Stokes Raman Spectroscopy of Infrared Multiphoton Excited Molecules," *J. Chem. Phys.*

J.-K. Wang, Y. Siegal, C.-Z. Lü, E. Mazur, and J. Reintjes, "The Role of Self-phase Modulation and Self-focusing in Transient Stimulated Raman Scattering in High-pressure Hydrogen Gas," *Optics Letters*.

P. Saeta, Y. Siegal, J.-K. Wang, and E. Mazur, "Femtosecond Carrier-induced Disorder of GaAs," *Phys. Rev. B* (submitted).

#### b. Papers Published in Refereed Journals

P. Saeta, J.-K. Wang, Y. Siegal, N. Bloembergen, and E. Mazur, "Ultrafast Electronic Disorder During Femtosecond Laser Melting of GaAs," *Phys. Rev. Lett.* **67**, 1023 (1991).

C.-Z. Lü, J. Goldman, S. Deliwala, K.-H. Chen, and E. Mazur, "Direct Evidence for  $n_1$ -mode Excitation in the Infrared Multiphoton Excitation of  $\text{SO}_2$ ," *Chem. Phys. Lett.* **176**, 335 (1991).

#### c. Books (and sections thereof) Submitted for Publication

J.-K. Wang, Y. Siegal, P. Saeta, N. Bloembergen, and E. Mazur, "Femtosecond, Electronically-Induced Disorder of GaAs," in *Ultrafast Phenomena VIII*, (Springer Verlag, 1992) (in press).

E. Mazur, J.-K. Wang, and Y. Siegal, "Femtosecond Nonlinear Optics of Semiconductors," *Proc. Army Sci. Conf.* (in press).

#### d. Books (and sections thereof) Published

P. Saeta, J.-K. Wang, Y. Siegal, N. Bloembergen, and E. Mazur, "Electronic Disorder During Femtosecond Laser Melting of GaAs," in *Technical Digest*, Quantum Electronics and Laser Science Conference, Anaheim, CA, May 1992.

K.Y. Lee, T. Chou, and E. Mazur, "Direct Optical Measurements of Capillary Wave Damping at Liquid-Vapor Interfaces," *Technical Digest*, Int. Quantum Electronics Conf., Vienna, June 1992.

J.-K. Wang, Y. Siegal, C. Lü, and E. Mazur, "Subpicosecond Stimulated Raman Scattering in High-pressure Hydrogen," *Technical Digest*, Int. Quantum Electronics Conf., Vienna, June 1992.

**g. Invited Presentations at Topical or Scientific/Technical Society Conferences**

E. Mazur, "Electronic Disordering During Femtosecond Melting of Gallium Arsenide," Quantum Electronics and Laser Symposium, Anaheim, CA, May 1992.

E. Mazur, Keynote Address: "Femtosecond Nonlinear Optics of Semiconductors," Army Science Conference, Orlando, Florida, June 1992.

**h. Contributed Presentations at Topical or Scientific/Technical Society Conferences**

E. Mazur, "Reflectivity and Second Harmonic Efficiency of GaAs During Femtosecond Melting," Ultrafast Phenomena Conference, Monterey, California, June 1990.

E. Mazur, "Collisional and Intramolecular Dynamics of Low Lying Vibrational States of Infrared Multiphoton Excited Molecules," International Quantum Electronics Conference, Anaheim, California, June 1990.

E. Mazur, "Dynamics of Vibrational Energy Transfer in IR Laser-excited Molecules Observed Using Nonlinear Spectroscopy," Interdisciplinary Laser Science Conference 1990, Minneapolis, September 1990.

E. Mazur, "Femtosecond Melting of GaAs Probed by Reflectivity and Second-harmonic Generation," 1990 Annual Meeting of the Optical Society of America, Boston, November 1990.

E. Mazur, "Tunable, Synchronized, High Energy, Femtosecond Laser Pulses with Gaussian Spatial Profile," 1991 Annual Meeting of the Optical Society of America, San Jose, November 1991.

E. Mazur, "Femtosecond, Electronically-Induced Disordering of GaAs," Ultrafast Phenomena Conference, Antibes, France, June 1992.

E. Mazur, "Subpicosecond Stimulated Raman Scattering in High-pressure Hydrogen," International Conference on Quantum Electronics '92, Vienna, Austria, June 1992.

E. Mazur, "Direct Optical Measurements of Capillary Wave Damping at Liquid-Vapor Interfaces," International Conference on Quantum Electronics '92, Vienna, Austria, June 1992.

**j. Graduate Students and Postdoctorals Supported under the JSEP for the Year Ending July 31, 1992**

Dr. Walter Mieher, Mr. Jay Goldman, and Mr. Shrenik Deliwala.

### **III. INFORMATION ELECTRONICS: CIRCUITS AND SYSTEMS**

#### **Personnel**

Prof. R.W. Brockett  
Assoc. Prof. J.J. Clark  
Prof. Y.C. Ho  
Dr. L. Mollamustafaoglu  
Dr. R. Sreenivas  
Dr. Z. B. Tang  
Asst. Prof. W. Yang  
Mr. C.H. Chen  
Mr. L.-Y. Dai

Mr. M. Deng  
Mr. D. Friedman  
Mr. I. Garai  
Mr. M. Gottardi  
Mr. W.G. Li  
Mr. N. Patsis  
Mr. N. Saxena  
Mr. L.Y. Shi

**III.1 Analog VLSI and Principal Component Analysis.** R.W. Brockett, J.J. Clark, W. Yang, and N. Saxena, Grant N00014-89-J-1023; Research Unit 9.

Since November 1991, we have been investigating adaptive, nonlinear, signal processing tasks and have focussed on the task of principal component analysis. Principal component analysis is a basic signal processing task that has important applications in data compression, noise rejection, and pattern recognition. In recent work by Brockett at Harvard University, we have described a system of nonlinear differential equations which can determine the eigenvalues of a sample covariance and thus be used for principal component analysis. While previous VLSI implementations of these types of adaptive signal processing tasks have utilized digital components, the characteristics of coupled differential equations and principal component analysis are well matched to the capabilities of analog VLSI. Currently, we are investigating alternative VLSI implementations which utilize novel analog circuitry and massively parallel architectures. A robust analog computing system offers potentially revolutionary improvements in speed, size, power consumption, and cost in comparison to traditional digital approaches. However, analog VLSI

implementations must be able to deal effectively with noise, limited dynamic range, imprecise component values, mismatched components, and accumulation of errors both at the circuitry and algorithmic level. Our research efforts have focussed on addressing these issues for the implementation of a robust analog computing system for principal component analysis.

Specifically, principal component analysis involves the computation of an  $N \times N$  sample covariance of a signal and subsequently determining the associated  $N$  eigenvalues of the sample covariance. Through a series of multiply and accumulate operations, we can compute the sample covariance matrix. This sample covariance matrix is used as the initial conditions for our system of nonlinear differential equations which will evolve in time to yield the eigenvalues which are sorted from largest to smallest. The corresponding eigenvectors can also be found using a related system of equations. Thus, a full implementation of a principal component analyzer will require two components, one for computing the sample covariance and one for implementing our system of nonlinear differential equations.

### **III.2 Analog VLSI Implementation of the Eigenvalue Finder. R.W. Brockett, J.J. Clark, W. Yang, and N. Saxena, Grant N00014-89-J-1023; Research Unit 9.**

An important aspect of the implementation of the dynamical systems which perform the matrix diagonalization is that of the effect of circuit inaccuracies on the convergence of the system. Examination of the equations indicates that, depending on the particular approach taken, our system requires the implementation of analog multipliers or exponentiation circuits, scaling circuits (i.e., multiplication by a constant), adders and integrators.

All these component circuits are quite common in the analog computing world. However, as is quite well-known, such circuits have limited accuracy (about 6 to 8 bits at best) which could severely affect the performance of the entire com-

putation. It is crucial that our implementation of the system of nonlinear equations behaves properly in the face of this level of precision. Another complication is the limited dynamic range of analog computing circuits, which could also affect the performance of the computing algorithm. In order to get an idea of the effect of limited accuracy and dynamic range on the entire computation, a simulation experiment was performed. A system of  $3 \times 3$  equations was simulated using MATLAB. Limited accuracy was introduced by simply truncating the result of each computation after the second decimal bit. Limited dynamic range was introduced by keeping the result of each computation within a certain range of values (for example, between 0.01 and 3 volts). The input values were restricted between 0.01 and 1 volts. The result obtained from simulations with these inaccuracies was then compared with that obtained from performing the same computation using 32 bit floating point operations. The performance of the system with the inaccuracies was qualitatively similar to that of the system without the inaccuracies.

Two approaches to the implementation of the equations are being examined. The first involves the use of analog multipliers while the second implements a transformed version of the equations which require exponentiators and summation circuits in place of the multipliers. Currently, we are working on the second approach and will begin work on the first approach in the near future.

The approach using exponentiators is promising as the operation of exponentiation (and consequently of logarithms) can be done quite naturally and simply in VLSI technology. Two approaches to its implementation are being considered: i) MOS Field Effect Transistors (this approach uses the exponential characteristic of a MOSFET in its subthreshold regime). ii) Bipolar junction (PN Junction Diode and Parasitic Bipolar Transistor).

A test chip with several bipolar transistor configurations and an MOS exponential circuit has been fabricated and is currently being tested. Once we know the

exponential characteristics of the fabricated devices and circuits, we will be able to design the multiplier more accurately.

Simulations show that the bipolar junction has a larger range of exponential behavior than the MOS circuit. So, while the chip is being tested, the bipolar junction transistor is being used for design simulations of the multiplier circuit. The logarithm circuit was designed using an opamp and a bipolar transistor. The output of two such circuits was fed into the inputs of an opamp adder, whose output was then exponentiated using a single bipolar transistor. Thus we get a current output which is a scaled multiplication of the current inputs. This design was simulated and was found to work for a suitable range of input values. The results have not been analyzed in much detail because the model for the bipolar transistor used in the simulation is not for parasitic bipolar transistors. Once the parameters for the parasitic bipolar transistor are obtained, a more realistic simulation will be performed, and the simulation results will be analyzed in more detail. One can avoid the need for logarithm operations if the logarithms of the entries of the matrix to be diagonalized are computed externally. Then the matrix differential equations need only require exponentiation operations.

### **III.3 Toda Lattice Sorter.** R.W. Brockett, J.J. Clark, W. Yang, and N. Saxena, Grant N00014-89-J-1023; Research Unit 9.

An interesting special case of the symmetric matrix diagonalization process occurs when the matrix to be diagonalized is diagonal but with its diagonal entries not sorted. The matrix differential equations will flow in such a way as to move away from the initial condition and then return to a diagonal matrix in which the diagonal entries are sorted. It can be shown that the matrix is at all times tri-diagonal, which greatly simplifies the connectivity required for its implementation. In fact one can implement this sorter (known as a "Toda" lattice) with a one-dimensional array of processing elements.

We have fabricated a CMOS integrated circuit which contains a 30-stage Toda lattice sorter as well as some test circuitry. This circuit uses the exponential form of the equations and will give us data on the performance of the approaches we are taking to the implementation of exponentiation. We have very recently received the fabricated circuits and will begin characterizing their performance in the near future.

**III.4 Massively Parallel Processor for Eigenvalue Computation.** R.W. Brockett, J.J. Clark, W. Yang, and N. Saxena, Grant N00014-89-J-1023; Research Unit 9.

As has been previously shown, the eigenvalues of a symmetric, positive definite matrix,  $H(0)$  can be found as the diagonal elements of the solution,  $H(\infty)$  to

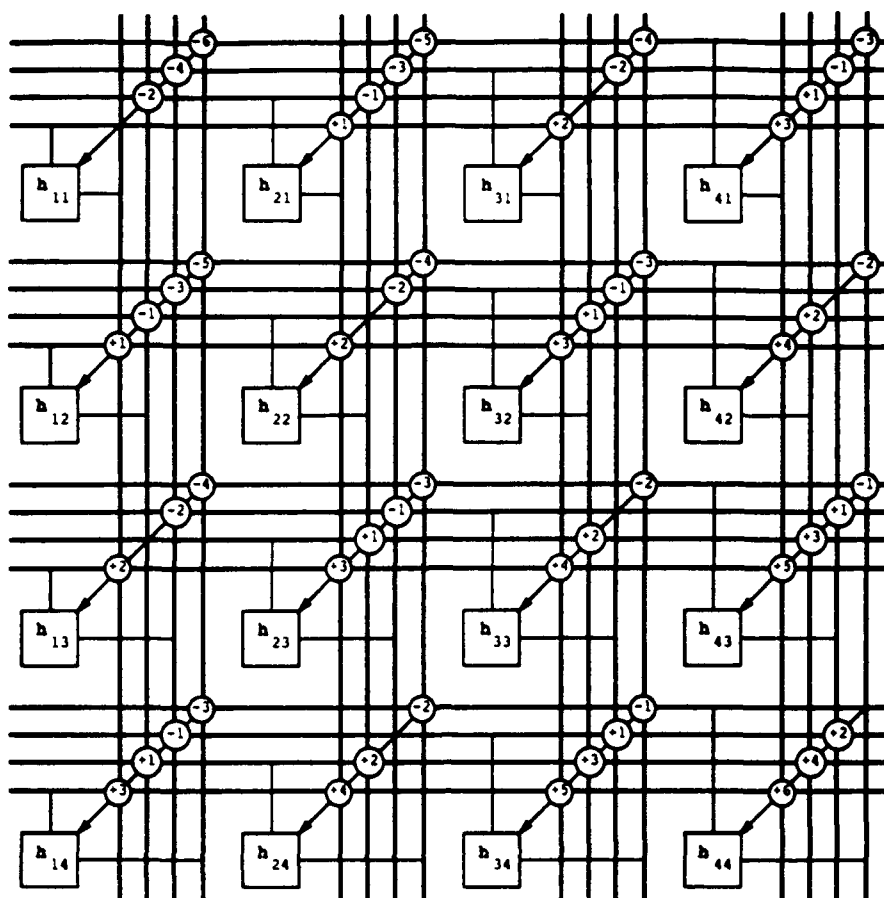
$$\dot{H} = [H, [H, N]]$$

where  $[A, B] = AB - BA$  and  $N$  is chosen to be diagonal with  $n_{ii} = i$ . Thus for each element in the matrix,  $h_{ij}$  we can write

$$\dot{h}_{ij} = \sum_{k=1}^n h_{ik} h_{kj} (i + j - 2k).$$

Notice that the computation of  $\dot{h}_{ij}$  requires the weighted sum of a series of analog-analog multiplications. Furthermore, notice that the computation of  $\dot{h}_{ij}$  does not require arbitrary communication capability but instead only requires communication within common column elements,  $h_{ik}$  and row elements,  $h_{kj}$ .

By exploiting this limited communications requirement, we can implement a massively parallel processor for performing principal component extraction (see Figure III.1). The elements,  $h_{ij}$  of a symmetric, positive definite matrix are loaded into the processor array as indicated. Then each value,  $h_{ij}$  is broadcast to common column and row elements through vertical and horizontal connections. The products of column and row elements are computed by processors at each location indicated



**Figure III.1.** A massively parallel processor for computing eigenvalues of a  $4 \times 4$  matrix.

by a circle. Thus, the value of  $\dot{h}_{ij}$  is computed as the indicated weighted sum of the products of row and column elements. When  $\dot{h}_{ij} = 0$  for every element in the array, the system has reached steady state, the off-diagonal elements will be 0, and the eigenvalues will be ordered from largest to smallest as the diagonal elements,  $h_{ii}$ .

**III.5 Pulse-Frequency Analog Computing.** R.W. Brockett, J.J. Clark, W. Yang, D.J. Friedman, and N. Saxena, Grant N00014-89-J-1023; Research Unit 9.

Analog information has typically been encoded as an analog charge, current, or voltage value which effectively limits the dynamic range in simple implementations to  $10^3$  due to noise and signal degradation. Recently, we developed

and demonstrated a pulse-frequency technique for robust encoding of wide-dynamic range analog information. In particular, we implemented a VLSI array of  $32 \times 32$  photosensors with a linear dynamic range of  $10^7$  in optical energy. By encoding analog information in the time domain or frequency domain, pulse-frequency encoding is much less susceptible to degradation and can extend the dynamic range of analog VLSI components. We are currently utilizing this pulse-frequency technique to implement high performance analog computing components.

We have recently begun the design of a wide-dynamic range analog multiplier based on pulse-frequency encoding. Specifically, we utilize the fact that the amount of charge accumulated by a CMOS switched capacitor integrator is proportional to the product of an analog input voltage and the number of clock cycles. Thus by utilizing an analog voltage-to-frequency converter to generate a clock frequency that is directly proportional to some analog input, it is possible to implement a two-quadrant analog multiplier with analog inputs and analog output. The accuracy of the pulse-frequency multiplier will be limited primarily by (i) parasitic charge injection induced by the switch and (ii) the maximum integration time which imposes a minimum clock frequency. A full four-quadrant multiplier can be implemented by using a more sophisticated CMOS switched capacitor integrator with additional control circuitry to represent negative values. In particular, the voltage-to-frequency converter needs to generate a clock frequency which is proportional to the absolute magnitude of the analog input and also provide an additional signal indicating the sign of the input value. Subsequently, this control signal can be used to conditionally reverse polarity of the input charge.

The pulse-frequency multiplier is well suited for integration into a massively parallel processor for principal component analysis. The processing components for each element of the matrix can be implemented by incorporating multiple input structures on a single CMOS switched capacitor integrator. Thus each input

structure provides input charge at a rate that is proportional to the product of an analog input voltage and an asynchronous clock frequency. Furthermore, the matrix elements,  $h_{ij}$  are stored as the charge on the integration capacitor of the CMOS integrators. By proper weighting of the input capacitors in each input structure, it is possible to implement directly the computation of  $\dot{h}_{ij}$  and the continual update of  $h_{ij}$ . Component block and transistor level simulations of the pulse-frequency multiplier and the massively parallel processor are currently being performed.

## **ANNUAL REPORT OF PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS**

### **c. Books (and sections thereof) Submitted for Publication**

D.J. Friedman and J.J. Clark, "A Sensorimotor System Architecture," in *Perceptual Robotics*, S.T. Venkataraman and S. Gulati, eds., Springer-Verlag, New York.

### **i. Honors/Awards/Prizes**

Roger W. Brockett, IEEE Control Systems 1992 Science and Engineering Award

Roger W. Brockett, Elected Member of the National Academy of Engineering

Woodward Yang, National Science Foundation Young Investigator Award, 1992

### **j. Graduate Students and Postdoctorals Supported under the JSEP for the Year Ending July 31, 1992**

Mr. D.J. Friedman, Mr. N. Saxena, and Mr. Massimo Gottardi

**III.6 Ordinal Optimization.** Y.C. Ho, R. Sreenivas, Z. Bo Tang, L. Molamustafaoglu, Grants N00014-89-J-1023, N00014-89-J-0093, NSF-CDR-88-03012, NSF-ESC-91-02346, DAAL-03-86-K-0171, DAAL-03-91-G-0194; Research Unit 10.

We have shown that the order of performance of discrete event dynamic systems (DEDS) under various parameter settings are relatively immune to estimation errors. Consequently, if we concentrate first on the determination of a subset of good, better, and best designs before evaluating the actual cardinal performance values, then we can often effect a great increase in speed of the optimization search [1]. During 1991-92 we further developed this approach with respect to

- (i) Study of the effect of correlation on ordinal optimization in multiple parametrically different but structurally similar simulations [2].
- (ii) Study of the use of adaptation in ordinal optimization. In particular, the use of genetic-like algorithms to help with ordinal search was investigated [3].

Application of this algorithm has been made to the optimal design of robot arms. The PI gave a lecture course in Washington, D.C. to personnel from the Army Concepts Analysis Agency and the Office of the Joint Chiefs of Staff on 5/29-30/92. Possible application of the ordinal optimization algorithm to a real logistics problem in the offices of JCS and to the war game simulation of the CAA are under discussion as a result of the lecture course.

**III.7 Infinitesimal Perturbation Analysis** Y.C. Ho, Grant ONR-N00014-89-J-1023; Research Unit 10.

A unified approach to IPA was completed. We now have a very complete story of the computational and analytical properties of IPA in the sensitivity calculation of DEDS performances [4-6] integrating the recent contributions to this topic from Russia (Gaivironski) and France (Bremaud).

### References:

1. Y.C. Ho, R. Sreenivas, and P. Vakili, 1992
2. M. Deng, Y.C. Ho, and J.-Q. Hu, 1992
3. Y.C. Ho, R. Sreenivas, and I. Garai, 1992
4. L.-Y. Dai and Y.C. Ho, 1992
5. L.Y. Shi, 1992
6. Gaivironski, L.Y. Shi, and R. Sreenivas, 1992

## ANNUAL REPORT OF PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

### a. Papers Submitted to Refereed Journals (and not yet published)

K. Budka and D.D. Yao, "Stochastic Monotonicity and Concavity Properties of Rate-based Flow Control Mechanisms," *IEEE Trans. on Auto. Control*.

K. Budka and D.D. Yao, "First- and Second-order Stochastic Properties of Token Bank Rate Control Throttles," *IEEE Trans. on Communications*.

L.-Y. Dai and Y.C. Ho, "Structural Infinitesimal Perturbation Analysis (SIPA) for Derivative Estimation in Discrete Event Dynamic Systems," *IEEE Trans. on Auto. Control*.

M. Deng, Y.C. Ho, and J.-Q. Hu, "Effect of Correlation Estimation in Ordinal Optimization," *Proceedings of the Winter Simulation Conference*.

A. Gaivironski, L.Y. Shi, and R. Sreenivas, "Augmented Infinitesimal Perturbation Analysis: An Alternate Explanation," *J. DEDS*.

Y.C. Ho, C. Cassandras, and M. Makhoul, "Parallel Simulation of Real Time System via the Standard Clock Approach," *J. IMACS*.

Y.C. Ho, L.Y. Shi, L.-Y. Dai, W.B. Gong, "Optimization of Discrete Event Dynamic Systems via Gradient Surface Method," *J. DEDS* 2(3); also in *Proceedings of the 30th IEEE Conference on Decision and Control*, pp. 104-109, 1991.

Y.C. Ho, R. Sreenivas, and I. Garai, "Hybrid Ordinal Optimizaiton," *Proceedings of IEEE Conference on Decision and Control*.

Y.C. Ho, R. Sreenivas, and P. Vakili, "Ordinal Optimization of DEDS," *J. DEDS* 2(2).

J.-Q. Hu and M.C. Fu, "Sample Path Properties of the G/D/m Queue," *European Journal of Operational Research*.

L. Mollamustafaoglu, "Parallel Simulation of Multiple Discrete Event Dynamic Systems," *Advances in Simulation* 92.

L.Y. Shi, "Approximate Analysis for Queueing Networks with Finite Buffers," *Queueing Systems*.

L.Y. Shi, "Discontinuous Perturbation Analysis," *IEEE Trans. on Auto. Control*.

L.Y. Shi, "Perturbation Analysis with Discontinuous Sample Performance

Function," *IEEE Trans. on Auto. Control*; also in *Proceedings of the Second Telecommunications Conference*, 1992.

L.Y. Shi, J.-Q. Hu and M.C. Fu, "Likelihood Ratio Methods via Conditional Monte Carlo and Splitting," Abstract submitted to ORSA/TIMS Joint National Meeting, May, 1992.

R. Sreenivas, "A Note on Deciding the Controllability of a Language K with Respect to a Language L," *IEEE Trans. on Auto. Control*.

R. Sreenivas, "On a Weaker Notion of Controllability of a Language K with Respect to a Language L," *IEEE Trans. on Auto. Control*.

Z.B. Tang, "Estimation of the Generalized Pareto Distribution with Finite Endpoint," *IEEE Trans. on Auto. Control*.

Z.B. Tang, "Partitioned Random Search to Global Optimization," *IEEE Trans. on Auto. Control*.

Z.B. Tang and L. Shi, "Note on 'Distributed Scheduling Based on Due Dates and Buffer Priorities' by S.H. Lu and P.R. Kumar," *IEEE Trans. on Auto. Control*.

P. Vakili, L. Mollamustafaoglu, and Y.C. Ho, "Massively Parallel Simulation of a Class of Discrete Event Systems," The 4th Symposium on the Frontiers of Massively Parallel Computation, sponsored by the IEEE Computer Society, NASA Goddard Space Flight Center, IEEE, to be held October, 19-21, 1992 in McLean, Virginia.

**b. Papers Published in Refereed Journals**

Y.C. Ho, Video Instructional Tape on Discrete Event Dynamic Systems, IEEE Educational Services Department.

R. Sreenivas, "Performance Analysis of the FDDI Protocol Using a Fluid Model," *Proceedings of the 26th Conference in Information Sciences and Systems*, Princeton, NJ, March 18th-20th, 1992.

W.-B. Gong and J.-Q. Hu, "The Maclaurin Series for the  $GI/G/1$  Queue," *J. Appl. Prob.* **29**, 176-194 (1992).

J.-Q. Hu, "Variance Properties of Sample Path Derivatives of Parametric Random Variables," *Operations Research Letters* **11**, 47-54 (1992).

**g. Invited Presentations at Topical or Scientific/Technical Society Conferences**

Y.C. Ho, ICIAM International Meeting, Washington, D.C., July 1991.

Y.C. Ho, Army High Performance Computing and Communication Workshop meeting, Washington, D.C., July 1991.

Y.C. Ho, Apparel Industry meeting, Harvard, August 1991.

Y.C. Ho, U. of Connecticut, E.E. Dept., September 1991.

Y.C. Ho, Boston University, November 1991.

L.Y. Shi, 1991 CDC, Brighton, U.K., December 1991

Y.C. Ho, Singapore SICICI'92 tutorial course, February 1992.

Y.C. Ho, Singapore SICICI'92 plenary address, February 1992.

Y.C. Ho, University of California at Santa Barbara, E.E. Dept., February 1992.

Y.C. Ho, Army Manufacturing Workshop, Army Research Office, NC, March 1992.

L.Y. Shi, 2nd Annual Communications Conference, Boca Raton, FL, March 1992.

R. Sreenivas, 26th Annual Conf. in Info. Sci. and Systems, Princeton, NJ, March 1992.

R. Sreenivas, University of Illinois, April 1992.

Y.C. Ho, Army Concepts Analysis Agency, Washington, D.C., May 1992.

R. Sreenivas, University of Colorado, May 1992.

Y.C. Ho, Imperial College Symposium, June 1992.



## IV. ELECTROMAGNETIC PHENOMENA

### Personnel

Prof. T. T. Wu  
Prof. R. W. P. King  
Dr. J. M. Myers  
Dr. H.-M. Shen

Mr. G. Fikioris  
Mr. D. K. Freeman  
Mr. V. Houdzoumis  
Ms. M. Owens  
Ms. B. H. Sandler

Research in the area of electromagnetic radiation is directed toward the solution of practical problems through the complete understanding of the underlying physical phenomena. This involves the coordinated application of modern analytical, numerical, and experimental techniques and the use of high-speed computers and precision instrumentation. Application is also made of modeling techniques and the principle of similitude. Most practically significant problems in the area are sufficiently complicated that extensive computation and measurement are often required to justify approximations that are usually necessary. Where possible, general formulas are obtained and verified experimentally so that the phenomenon under study can be understood physically in analytical form and not just as a set of numbers.

The researches are concerned primarily with the properties of antennas and arrays and of the electromagnetic fields they generate in various practically important environments that lead to difficult problems with complicated boundary conditions. Examples include the properties and fields of dipoles, insulated antennas, traveling-wave antennas and arrays, crossed dipoles, and loops when located near the boundary between two media such as air and the earth or sea, or the oceanic crust and sea water; microstrip patch antennas and Beverage-type antennas for over-the-horizon radar; and resonant circular and other closed-loop arrays of

parallel dipoles in free space and on the earth or sea. The field near the boundary includes lateral electromagnetic waves with unusual properties that require detailed study for important applications in remote sensing from the surface of the earth or sea, the arctic ice or the sea floor, and in horizontally-layered media. Also of theoretical and practical interest are the generation, propagation, and reception of lateral electromagnetic pulses along boundaries; and solitary electromagnetic pulses with slow rates of decay.

#### **IV.1 Electromagnetic Field of Dipoles and Patch Antennas on Microstrip.**

R. W. P. King, Grant N00014-89-J-1023; Research Unit 11.

Microstrip antennas consist of variously shaped and excited conducting strips or patches on the dielectric substrate. Their primary function is to generate a significant electromagnetic field at distant points. This field is the superposition of contributions from infinitesimal elements of current or unit electric dipoles in the patch. The unit dipole has an electric moment  $Ih = 1$  Am; when multiplied by  $I(x'') dx''$ , the dipole is an element of a patch antenna. The complete field of such an antenna is obtained by an integration over the current distribution. This has not been determined analytically for commonly used shapes. In practice, it is obtained by numerical methods or by an educated guess. Since the far field is not sensitive to the details of the current distribution, a usually adequate picture of the radiating properties of a patch antenna can be obtained in this manner.

Formulas for the complete electromagnetic field of a unit horizontal electric dipole on the surface of a dielectric-coated conductor (microstrip) were derived last year [1]. They have been used here [2] to derive expressions for the complete far field of an  $x'$ -directed element at an point  $\rho, \phi', z'$  in the air; this includes the space wave and the surface wave. From these, the corresponding formulas for the far field of an antiresonant rectangular patch antenna with an assumed sinusoidal current

distribution have been derived.

#### References:

1. R. W. P. King, "The Electromagnetic Field of a Horizontal Electric Dipole in the Presence of a Three-Layered Region," *J. Appl. Phys.* **69**(12), 7987-7995 (1991).
2. R. W. P. King, "Electromagnetic Field of Dipoles and Patch Antennas on Microstrip," *Radio. Sci.* **27**(1), 71-78 (1992).

#### IV.2 The Circuit Properties and Complete Fields of Wave Antennas and Arrays. R. W. P. King, Grant N00014-89-J-1023; Research Unit 11.

The wave antenna is important for communication between points on or near the surface of the earth and especially as a versatile backscatter radar capable of detecting targets in the whole range from distant and high-flying to quite close and low-flying. For distant targets the curvature of the earth makes the use of reflection from the ionosphere a necessary complication. Transmission to the 300 to 500 km distant ionosphere requires quantitative knowledge of the field at all upward angles. When the target is not an ICBM thousands of kilometers away but a cruise-missile launched by a submarine or a low-flying drug-carrying aircraft within 1000 km of the radar transmitter-receiver, reflections from the ionosphere are best supplemented by the surface wave. This is unaffected by geomagnetic storms and independent of skip distances.

The wave antenna consists of a long horizontal wire in air electrically very close to the surface of the earth or sea and so terminated that a pure traveling wave propagates along it in both the transmitting and receiving modes. This can be accomplished with suitable ground connections in series with a resistor as in the familiar Beverage antenna. Alternatively, each termination may be a resistor in series with a horizontal, quarter-wave monopole to form a horizontal-wire antenna. With either form, the generator-receiver is located adjacent to the resistor at one

end. The wave antenna was analyzed previously [1] subject to the condition  $\rho^2 \gg z'^2$  where  $\rho$  is the radial distance from the source and  $z' = -z$  is the height of the point of observation above the surface of the earth.

In a recent investigation [2], the complete electromagnetic field generated by a wave antenna—including both the space wave and the surface wave at all points in the air and on the surface of the earth or sea—has been derived. A knowledge of this complete field is essential for an over-the-horizon radar that makes use of both ionospheric reflection for detecting distant high-flying targets and the surface wave for detecting near and low-flying targets.

Although the electromagnetic field of a unit electric dipole is smaller by the factor  $|k_2/k_1|$  when it is horizontal at a small height  $d$  than when it is vertical, a long traveling-wave antenna with a very substantial directive gain that can approximate or exceed the ratio  $|k_1/k_2|$  can be constructed of horizontal elements. Indeed, an array of broadside and collinear wave antennas can provide an electromagnetic field of much greater intensity and at much lower constructional cost than can be achieved with vertical monopoles alone. This is not obvious from the earlier analysis [1] since it determined only the surface-wave field of a single Beverage or horizontal-wire antenna.

It is also possible to combine a radial array of individually directive wave antennas with a vertical monopole to obtain a useful omnidirectional antenna that generates a powerful surface wave combined with a significant space wave. In [2], the design of such an array is presented. It consists of a vertical monopole and  $N = 10$  horizontal wave antennas at a small height  $d = 45$  cm over the earth. No ground connections are required. It is shown that the use of an array of horizontal wave antennas with a vertical monopole in place of the usual grounding network not only increases the space wave but uses the power ultimately dissipated in the earth to generate a large and useful surface wave.

In some applications in radar and in point-to-point communication, a directive array is preferred over an omnidirectional one. In such cases, an antenna that radiates a large field within a specified angle and a small field in all other directions is advantageous. Such an array is readily obtained by a simple modification of the omnidirectional array discussed above. Other combinations of vertical monopoles and horizontal wave antennas have interesting and useful characteristics. An example is a highly directive broadside array in which each element is a single vertical antiresonant monopole in series with a single horizontal wave antenna. A base-insulated resonant dipole is used as a parasitic reflector for each vertical element.

#### References:

1. R. W. P. King, "The Wave Antenna for Transmission or Reception," *IEEE Trans. Antennas Propagat.* AP-31(6), 956-965 (1983).
2. R. W. P. King, "The Circuit Properties and Complete Fields of Horizontal-Wire Antennas and Arrays over Earth or Sea," *J. Appl. Phys.* 71(3), 1499-1508 (1992).

**IV.3 The Propagation of a Gaussian Pulse in Sea Water.** R. W. P. King, B. H. Sandler, and M. Owens, Grant N00014-89-J-1023 and Raytheon Co. (under Contract N61533-90-C-0080 with ONR, Annapolis Detachment); Research Unit 11.

The propagation of electromagnetic waves in sea water is much more complicated than in lake water because the attenuation and phase constants are practically equal and both depend strongly on the frequency in a nonlinear manner. The interesting question arises: How does a single pulse progress in sea water? Is such a pulse a useful vehicle for remote sensing in the ocean? These questions can be investigated conveniently with a Gaussian pulse of current applied to a horizontal electric dipole on the surface of the sea. The Gaussian pulse is essentially a low-frequency pulse in the sense that the amplitudes of the constituent frequencies decrease very rapidly with increasing frequency. It is clearly well-suited to propaga-

tion in sea water where the exponential attenuation decreases with the frequency. When a Gaussian pulse is applied to a horizontal electric dipole on the surface of the sea, an electromagnetic pulse is generated that propagates upward into the air, downward into the sea, and horizontally along the boundary in a surface wave. Of interest here is the pulse propagating vertically downward and impinging, for example, on a horizontal metal cylinder. Can the cylinder be detected by observing the backscattered pulse?

Detailed quantitative information has been obtained for the properties of a Gaussian pulse propagating in sea water [1]. Of particular significance are the following points: 1) The amplitude of the propagating pulse decreases very rapidly with distance. 2) The shape of the pulse changes continuously with distance from the initial Gaussian shape to that of the time-derivative of the Gaussian. 3) The velocity of propagation of electromagnetic waves in sea water is frequency-dependent, decreasing with frequency. As the pulse propagates, the higher frequencies in its spectrum are more rapidly attenuated than the lower frequencies so that the higher-frequency content of the pulse decreases rapidly and with it the velocity of propagation of the pulse. 4) The apparent velocity of propagation of the maximum magnitude of the Gaussian pulse is anomalous. Because of the change in shape from the Gaussian to that of the derivative, the maximum of the pulse moves backwards for a short time. Actually all components move forward, only the maximum of their sum moves backwards.

To study the possible use of such a pulse in the detection of scattering obstacles, a direct transmission-reflection method without the intermediary of surface waves has been used. This makes use of a horizontal electric dipole in the form of an insulated conductor with the length  $2h$  terminated in bare ends. The dipole is electrically short for all frequencies involved in the Gaussian current pulse that is generated in it. The electromagnetic-field pulse travels vertically down into the sea.

It induces a current in a metal cylinder with the length 100 m and cross-sectional diameter 12.5 m located at a depth  $z = 100$  m. The current in the cylinder radiates an electromagnetic field in all directions in the sea including upward. The signal reaching a receiver adjacent to the transmitting dipole is the means for detecting the cylinder.

The shape and amplitude of the pulse reflected by the cylinder depends on the spectrum of frequencies involved and, therefore, on the width of the incident pulse. The current induced in the cylinder by each component of frequency is given in [2]. In the general case, the field scattered by each component of frequency has to be determined as in [1] and then summed over all frequencies. In a preliminary study this step can be avoided if the range of relevant frequencies is restricted to those for which the length of the cylinder is electrically short in sea water. Gaussian pulses with widths  $2t_1 \geq 0.1$  sec satisfy this condition. For them, the current induced in the cylinder has the same frequency dependence as the incident field so that the scattered field will also have this dependence. This means that an incident Gaussian-field pulse should be scattered as a Gaussian-field pulse.

If significant higher frequencies are present, the induced current becomes frequency-dependent and the scattered field is modified. Actually the induced current distribution differs little from the parabolic shape for electrically much longer scattering elements. The principal difference is an increase in the amplitude of the induced current as the scatterer approaches the resonant length near  $\beta_1 h = \pi/2$ . It follows that the range of pulse widths can be decreased to  $2t_1 = 0.01$  sec with the understanding that a scattered pulse will preserve the shape of the incident-field pulse quite accurately, but that the actual scattered-field amplitude should be somewhat greater than that calculated using the approximate current.

It has been found that a cylinder at a depth of 100 m is detectable with a Gaussian pulse of width  $2t_1 = 0.01$  sec, but not without a complicated cancellation

of the large direct field when a Gaussian pulse of width  $2t_1 = 1$  sec is used. A complete investigation of a range of relevant depths and pulse widths can be made. However, for pulses shorter than  $2t_1 = 0.01$  sec, the general formula for the current induced in the cylinder must be used and, since this is frequency-dependent, the response to an incident pulse requires numerical evaluation.

#### References:

1. R. W. P. King, "The Propagation of a Gaussian Pulse in Sea Water and Its Application to Remote Sensing," *IEEE Trans. Geosci. & Remote Sensing*, submitted for publication.
2. R. W. P. King, "Lateral Electromagnetic Waves from a Horizontal Antenna for Remote Sensing in the Ocean," *IEEE Trans. Antennas Propagat.* AP-37(10), 1250-1255 (1989).

#### IV.4 The Propagation of a Low-Frequency Burst in Sea Water. R. W. P. King, B. H. Sandler, and M. Owens, Grant N00014-89-J-1023 and Raytheon Co. (under Contract N61533-90-C-0080 with ONR, Annapolis Detachment); Research Unit 11.

The study of the propagation of single Gaussian pulses in sea water [1]—discussed under Topic IV.3—has been extended to include the propagation in sea water of a short burst of oscillations when its amplitude is limited by a Gaussian envelope. In particular, a complete analysis has been made [2] of the propagation in sea water of a burst of 25 cycles at  $f \sim 25$  Hz with amplitudes limited by a Gaussian envelope with the half-width  $t_1 = 0.5$  sec. The properties of the burst in transmission are governed in part by the Gaussian envelope, in part by the burst of oscillations. The most important characteristic is the very rapid decrease in the overall amplitude due to the electrically short distances involved and the initial  $1/z^3$  dependence on distance. Owing to the very low frequencies involved in the burst and the spectrum of the envelope, the exponential attenuation is not great.

Just as for the isolated Gaussian pulse [1], the apparent continuity of Gaussian

shape is misleading. Actually, the initial burst begins with a Gaussian envelope but the entire configuration changes rapidly to its time-derivative. In the process the maximum of the burst shifts to the initial maximum of the time-derivative. The backward movement of the maximum can be observed but this is much more difficult owing to the oscillations; also it is much more restricted to very short distances. A careful study of the numerical evaluation of the amplitudes of the individual oscillations shows that the apparent velocity of propagation  $v_a = z/t$  of the maximum of the envelope decreases from large values near  $z' = (\mu_0 \sigma_1 / 2t_1)^{1/2} z = 0.1$  to an approximately constant value of the order of magnitude of the phase velocity for a steady-state traveling wave in sea water at  $f \sim 25$  Hz. This behavior differs from that of the single Gaussian pulse which continuously loses higher frequencies from its spectrum as it travels in sea water and, hence, advances more and more slowly. The burst has primarily the properties of the 25 Hz oscillations at all distances.

Primary interest is in the electric field observed at a receiver on the air-sea surface near the transmitting dipole. As for the single Gaussian pulse, it is assumed that the back-scattered field is approximately the field incident on the scatterer but reversed in direction. The scattered burst is smaller than the direct burst observed at the receiver on the surface by a factor of the order  $10^{-4}$ . It arrives at the receiver while the direct burst is still rising to its maximum. If the direct burst can be balanced out in its entirety at the receiver, the scattered burst is sufficiently large to be detectable.

#### References:

1. R. W. P. King, "The Propagation of a Gaussian Pulse in Sea Water and Its Application to Remote Sensing," *IEEE Trans. Geosci. & Remote Sensing*, submitted for publication.
2. R. W. P. King, "The Propagation of a Low-Frequency Burst in Sea Water and Its Application to Remote Sensing," *IEEE Trans. Geosci. & Remote Sensing*, submitted for publication.

**IV.5 The Propagation of a Radar Pulse in Sea Water.** R. W. P. King, T. T. Wu, M. Owens, and B. H. Sandler, Grant N00014-89-J-1023 and Raytheon Co. (under Contract N61533-90-C-0080 with ONR, Annapolis Detachment); Research Unit 11.

Conventional radar transmits and receives wave packets that approximate finite sections of a continuous-wave field. In air, these propagate with no change in shape since all frequencies in the spectrum of the modulated pulse travel with the velocity of light. When a similar wave packet is transmitted in sea water, a much more complicated phenomenon occurs because the medium is dissipative and dispersive so that the wave number is complex and not linear in the frequency. As a consequence, the rise time and, with it, the shape of the wave packet are greatly modified as the pulse travels in the attenuating and dispersive salt water. In a new study, the propagation of wave packets has been investigated when the carrier frequency is sufficiently low to permit a significant distance of travel before the amplitude becomes too small to provide a detectable signal.

As a necessary preliminary to the determination of the electromagnetic field scattered by a metal cylinder submerged in the ocean, the propagation of a low-frequency pulse with a rectangular envelope has been evaluated numerically as a function of the distance of travel [1]. The electric fields generated by an electrically short dipole in sea water excited by a wave packet of 25.5 cycles at 25.5 Hz reveal a complicated behavior as the packet penetrates to increasing depths. The shape of the wave packet is increasingly altered with distance of travel. It follows that the received signal is quite different from the transmitted signal when distances are large.

To understand the numerically evaluated results, an analytical investigation to explain the computed properties was carried out. Specifically, the propagation in sea water of an electromagnetic field in the form of a semi-infinite wave train or a radar pulse generated by an electric dipole has been investigated analytically

for low frequencies. In the resulting paper [2], the frequency-domain formula for the downward-traveling field of a horizontal electric dipole excited by a sinusoidally modulated electric-current pulse is Fourier transformed to obtain an explicit expression for the field at any distance in the time domain. Specific application is made to a wave packet of 25.5 cycles in a time duration of one second. The amplitude and phase velocity of the wave packet are determined together with the amplitudes of the initial and final precursors. Graphs are displayed and discussed for a range of distances; these show that the amplitude of the wave packet decays more rapidly than the amplitudes of the precursors.

Supplementing the recent study by Oughston [3] which obtains "an asymptotic description for large values of the propagation distance," the present study provides a complete formula for the outward-traveling field both near and far in the equatorial plane of a dipole source. For possible application to the detection of targets in the ocean with conventional radar techniques instead of lateral waves as described in [4], the carrier frequency  $f_0$ , the pulse length  $2t_1$ , and the repetition rate must be selected with due consideration of the signal velocity and attenuation of the wave packet and of its distortion due to the leading- and trailing-edge precursors. These latter are attenuated with distance much more slowly than the wave packet and ultimately dominate the advancing pulse.

## References:

1. R. W. P. King, "Scattering of a Cylinder Submerged in the Ocean: The Propagation of a Low-Frequency Rectangular Pulse," *Radio Sci.*, submitted for publication.
2. R. W. P. King and T. T. Wu, "The Propagation of a Radar Pulse in Sea Water," *J. Appl. Phys.*, submitted for publication.
3. K. R. Oughston, "Pulse Propagation in a Linear Causally Dispersive Medium," *Proc. IEEE* **79**, 1379-1390 (1991).
4. R. W. P. King, "Lateral Electromagnetic Waves from a Horizontal Antenna for

Remote Sensing in the Ocean," *IEEE Trans. Antennas Propagat.* AP-37(10), 1250-1255 (1989).

**IV.6 Radiation of Electromagnetic Waves from a Tether in the Ionosphere to the Surface of the Earth.** R. W. P. King, Grant N00014-89-J-1023 and Raytheon Co. (under Contract N61533-90-C-0080 with ONR, Annapolis Detachment); Research Unit 11.

The possibility of transmitting electromagnetic waves from an antenna attached to an orbiting space shuttle to the surface of the earth has been suggested. The antenna generating the electromagnetic field would consist of a vertical wire (the tether), driven with the space shuttle as ground. The electromagnetic aspects of the problem have been examined with available knowledge as the basis. Because the existing theory of the properties of the ionosphere and of antennas moving in it is approximate and complicated, quantitative results can be obtained only in terms of a relatively simple model. The specific problem investigated is the electromagnetic field on the surface of the earth generated by currents in a vertical antenna moving in the F-layer of the ionosphere at a height of 400 km. The length of the antenna is 4 km. It is driven at its upper end by a generator voltage  $V_0$  against the space shuttle as a ground. The ionosphere is assumed to extend from a height of 150 km to infinity as a homogeneous medium. It is given a sharp boundary with air as a simplification of the gradual layered boundary between 100 and 200 km.

The properties of the ionosphere and three types of propagating waves have been examined for two frequency ranges: VLF ( $9 \leq f \leq 30$  kHz) and ELF ( $30 \leq f \leq 300$  Hz). Electromagnetic plasma waves and the Whistler mode propagate in the entire VLF band, and Alfvén waves in the ELF band. With the help of available approximate formulas, it is shown that a measurable incident electric field can be maintained on the surface of the earth.

**IV.7 Electromagnetic Fields of Vertical and Horizontal Magnetic Dipoles in and over the Sea.** R. W. P. King and M. Owens, Grant N00014-89-J-1023 and Raytheon Co. (under Contract N61533-90-C-0080 with ONR, Annapolis Detachment); Research Unit 11.

Owing to the symmetry of Maxwell's equations in free space, the complete electromagnetic field of the magnetic dipole can be obtained from that of the electric dipole with the simple substitutions:  $\mathbf{E}' = \mathbf{B}/\mu_0$  and  $\mathbf{B}' = -\epsilon\mathbf{E}$ , where  $\mathbf{E}$  and  $\mathbf{B}$  are the fields of the electric dipole,  $\mathbf{E}'$  and  $\mathbf{B}'$  the fields of the magnetic dipole. When an electric or magnetic dipole is near the plane boundary between two electrically different regions, the electromagnetic fields generated by the electric and magnetic dipoles are no longer simply related by these complementary formulas. This is a consequence of the fact that the boundary conditions for the electric and magnetic fields on the boundary between the two different regions are not the same. All tangential components are continuous, but the normal component of the electric field is discontinuous while the normal component of the magnetic field is continuous.

A complete and detailed analysis has been made of the electromagnetic fields generated by horizontal and vertical electric dipoles near a plane boundary between electrically different regions such as air and sea water [1] (See Topic IV.9). The derivations are complex and elaborate. In order to obtain the corresponding formulas for the fields of magnetic dipoles, two alternatives are available. One is to parallel the procedures carried out for the electric dipoles. The other is to combine the fields of electric dipoles to obtain the field of a small square constructed of electric dipoles, each with the electric moment  $Il$ , and to replace this by the equivalent magnetic moment  $Vl = (i\omega\mu_0 l) \times (Il) = i\omega\mu_0 l^2 I$ . Neither procedure is simple, but the latter is less complicated in that it involves no new integrals that need to be evaluated.

This latter approach is presently being carried out. The  $y$ -directed magnetic

dipole is represented by a square loop of electric dipoles; its field is the vector sum of the fields of the four dipoles. In order to explore the procedure and check its accuracy, it has been applied first to the fields of isolated electric dipoles, and the corresponding known field of the magnetic dipole has been successfully derived. Work is currently underway to derive the six components of the field of a  $y$ -directed horizontal magnetic dipole with its center at a height  $d$  in air over the surface of the earth or sea.

**Reference:**

1. R. W. P. King, M. Owens, and T. T. Wu, *Lateral Electromagnetic Waves: Theory and Applications to Communications, Geophysical Exploration, and Remote Sensing*, Springer-Verlag, New York (1992).

**IV.8 The Detection of Dielectric Spheres Submerged in Water.** R. W. P. King and S. S. Sandler, Grant N00014-89-J-1023 and the Small Business Administration under the SBIR Program in collaboration with Geo-Centers, Inc., and the U.S. Army Medical Branch; Research Unit 11.

The use of lateral electromagnetic waves to locate buried or submerged metal objects in the earth or sea with the horizontal electric dipole as the source has been described [1]–[3]. A related problem is the corresponding search for *dielectric* objects embedded in a general dissipative medium. Examples are plastic mines in the ocean and fragments of exploded plastic land mines embedded in human flesh. The important difference between the remote sensing for metal and plastic targets is the inverse nature of the relative magnitudes of the wave numbers characteristic of electromagnetic wave propagation in the ambient medium and in the embedded target. For simplicity the target can be taken to be a sphere consisting of air bubbles or plastic embedded in lake water, sea water or human flesh. The purpose of the study is to investigate the possibility of locating dielectric spheres in water or flesh by means of observations made on the boundary surface in the air.

The source is a horizontal electric dipole in the air on its boundary with the ambient medium that contains the target. It generates an electromagnetic field that propagates in the air along the boundary as a surface wave of a type known as a lateral wave. The amplitude fronts of the field in the earth or water propagate vertically downward; the phase fronts travel at an angle. It is this field that is incident on a target located at a depth  $z$ . In practice the field is not maintained by an infinitesimal unit dipole, but by a center-driven antenna located parallel to and at a small height in the air above the plane boundary. The source is, in effect, a center-driven eccentrically insulated dipole. If the dipole antenna is adjusted in length to be resonant and the height is carefully chosen, the driving-point impedance will be resistive and, hence, readily matched to a feeding transmission line.

The basic theory has been developed [4] for the use of horizontal electric dipoles on the surface of a dissipative region to detect small dielectric spheres embedded at some depth in that region. Since interest is in the detection of quite small targets and the scattering by dielectrics is much weaker than by metals, it is necessary to make use of quite high frequencies in order to have adequate resolving power. It has been shown that detectable reflected signals can be generated with acceptable power so that it should be possible to locate small dielectric objects with suitably designed apparatus.

#### References:

1. R. W. P. King, "Scattering of Lateral Waves by Buried or Submerged Objects. I. The Incident Lateral-Wave Field," *J. Appl. Phys.* **57**(5), 1453-1459 (1985).
2. R. W. P. King, "Scattering of Lateral Waves by Buried or Submerged Objects. II. The Electric Field on the Surface Above a Buried Insulated Wire," *J. Appl. Phys.* **57**(5), 1460-1472 (1985).
3. R. W. P. King, "Lateral Electromagnetic Waves from a Horizontal Antenna for Remote Sensing in the Ocean," *IEEE Trans. Antennas Propagat.* **AP-37**(10), 1250-1255 (1989).

4. R. W. P. King and S. S. Sandier, "The Detection of Dielectric Spheres Submerged in Water," *IEEE Trans. Geosci. & Remote Sensing*, accepted for publication.

**IV.9 Lateral Electromagnetic Waves (book).** R. W. P. King, M. Owens, and T. T. Wu, Grant N00014-89-J-1023; Research Unit 11.

A new 746-page book entitled *Lateral Electromagnetic Waves: Theory and Applications to Communications, Geophysical Exploration, and Remote Sensing*, by R. W. P. King, M. Owens, and T. T. Wu has been published [1]. This book analyzes electromagnetic radiation due to sources located near a boundary between two media like air and earth or air and sea. Such radiation has properties that are different from those familiar from the study of incident plane waves. Of these, the most important property is a surface wave of a type known as a lateral wave, which propagates along the boundary. (Analogous waves that occur in seismology are called head waves.) Electromagnetic lateral waves have many applications which are treated in this book. They include the investigation of the properties of the Earth's mantle, radio communication with submarines and over the Earth's surface, remote sensing and over-the-horizon radar. More general situations, in which there are more than two layers, are also treated. These include the effect of sediment in the study of the oceanic crust and of the Arctic ice in the detection of submerged submarines. The analysis of microstrip circuits and antennas involves three layers, namely, the air, the dielectric substrate, and the conducting base.

The systematic study presented in this book begins with the rigorous analytical derivation of the complete set of electromagnetic waves—spherical waves and lateral waves—generated by horizontal and vertical dipoles near or on the plane boundary between two half-spaces with quite different characteristic wave velocities. Formulas are first derived in the form of general integrals, which constitute the exact solution. From these, simple continuous formulas are obtained that are

accurate and valid everywhere except very close to the source. These simple and practical formulas are available in a book for the first time.

The book contains the results of current and past researches on lateral electromagnetic waves that have been supported in large part by the Joint Services Electronics Program. It is characterized by its broad generality and mathematical exactitude, and by its detailed treatment of important practical applications. It should be a very useful tool and comprehensive reference for researchers in atmospheric physics, geophysics, electrical engineering, applied mathematics, and mathematical physics.

#### Reference:

1. R. W. P. King, M. Owens, and T. T. Wu, *Lateral Electromagnetic Waves: Theory and Applications to Communications, Geophysical Exploration, and Remote Sensing*, Springer-Verlag, New York (1992).

#### IV.10 Theoretical Study of Electromagnetic Pulses with a Slow Rate of Decay. T. T. Wu, J. M. Myers, H. M. Shen, R. W. P. King, and V. Houdzoumis, Grant N00014-89-J-1023 and Army LABCOM Contract DAAL02-89-K-0097; Research Unit 11.

The interesting possibility of generating electromagnetic pulses of finite total radiated energy that decreases with distance much more slowly than the usual  $r^{-2}$  has been investigated both theoretically (this topic) and experimentally (see Topic IV.11). Such pulses are conveniently referred to as electromagnetic (EM) missiles [1]. Theoretical work during the past year has been concerned with the scattering of EM missiles from various objects. A paper has been published [2] that analyzes the two-dimensional problem of the scattered energy flux due to an EM missile incident upon an infinite circular perfectly conducting cylinder. The analysis is based on an expansion of the field in terms of Bessel functions. The paper also treats the incident missile locally as a plane-wave transient impinging on the point of specular reflection, and applies geometrical optics to compute the reflection. This

"geometric approximation" is found to agree exactly with the explicit calculation of fields, thus justifying both the local approximation by a plane wave and the use of geometrical optics. The geometrical method is generalizable to a broad class of convex objects with nonzero, bounded surface curvature. The result for the sphere is that the backscattering preserves linear polarization, reverses circular polarization, and returns an energy flux proportional to  $r^{-(2+\epsilon)}$ , where the incident missile delivers a flux  $r^{-\epsilon}$ . The backscattered energy varies as the square of the radius of the sphere.

The  $r^{-2-\epsilon}$  behavior of the energy of EM missiles scattered from spheres differs drastically from the  $r^{-\epsilon}$  dependence of the backscattered energy on range from a flat plate. The question arises whether there are objects that exhibit a scattering behavior that is intermediate between that for round and flat objects. A theoretical study has shown that such objects do exist. To study their properties, it is convenient to start in two dimensions, where round objects echo as  $r^{-1-\epsilon}$ , in place of the  $r^{-2-\epsilon}$  for three dimensions. In two dimensions, the generalized super-ellipse defined as  $|x|^\nu + |y|^\nu = 1$  is such an object when  $\nu > 2$ . The range dependence of the energy backscattered by a super-ellipse illuminated by an EM missile has been derived and shown to be intermediate between the two previously reported cases. An asymptotic formula for the backscattered energy has also been derived. This formula is valid for large distances between the source and scatterer and is uniform in  $\epsilon$ . It shows that the qualitative behavior of the backscattered energy depends on the quantity  $q = 1 - 2\nu^{-1} - \epsilon$ . In particular, for  $q > 0$ , the energy attenuates as  $r^{-1+\nu q/(\nu-1)}$ , whereas for  $q < 0$  it attenuates as  $r^{-1+q}$ . When  $q = 0$ , the energy attenuates as  $r^{-1} \ln r$ . The behavior in the transitional region near  $q = 0$  can also be obtained from the asymptotic formula. Similar results can be shown for three-dimensional super-ellipsoids, where the characteristic quantity is then  $q = 2 - 4\nu^{-1} - \epsilon$ .

## References:

1. T. T. Wu, "Electromagnetic Missiles," *J. Appl. Phys.* **57**(7), 2370-2373 (1985).
2. M. F. Brown and J. M. Myers, "Scattering of Electromagnetic Missiles by Convex Metal Objects," *J. Appl. Phys.* **70**(11), 7176-7178 (1991).

### IV.11 Experimental Study of Electromagnetic Pulses with a Slow Rate of Decay. H.-M. Shen, R. W. P. King, and T. T. Wu, Grant N00014-89-J-1023 and Army LABCOM Contract DAAL02-89-K-0097; Research Unit 11.

An improved L-antenna has been designed to measure a long pulse or CW electromagnetic field. The new design makes use of a distributed resistance to eliminate the undesirable multiple parasitic reflections. Two methods have been employed—one more accurate than the other—to analyze a two-wire parallel transmission line with distributed resistance and, based on the results of these theoretical models, L-antennas with a distributed resistance have been constructed. Measurements made with the improved L-antennas clearly show that the presence of the distributed resistance significantly reduces the reflected pulses. The design based on the more accurate of the two methods produces the better results.

Also during this reporting period, laser-triggered electrical discharges have been reviewed as a mechanism for generating EM missiles [1]. Since 1988, Auston, Zhang, and their coworkers at Columbia University [2] have used laser-triggering to provide electromagnetic current over an element of area on the order of  $1 \text{ cm}^2$ , with demonstrated subpicosecond electromagnetic pulses free of any carrier, some with bandwidths of  $10^{12} \text{ Hz}$ , and some, of less bandwidth, with peak power densities of  $64 \text{ W/cm}^2$ . These advances have been outlined in [1] and some of the problems and prospects for coordinating many such elements are discussed. A design for a launcher of electromagnetic missiles for a target 100 km distant is discussed in terms of the time dependence of a current pulse over an aperture. Two issues in implementing this design are: 1) to provide the required current distribution over a

small surface element; and 2) to coordinate many such elements in an array. A novel approach for coordinating pulses, based on an adaptive technique already used for pulsed lasers, is proposed as a means for measuring and correcting critical timing discrepancies in an array of pulse generators; beam focusing can also be controlled in this way.

#### References:

1. J. M. Myers and H.-M. Shen, "Experiments Using Laser-Triggered Electrical Discharges to Generate Electromagnetic Missiles," SPIE Proceedings, Vol. 1629, Intense Microwave and Particle Beams III, 274-280 (1992).
2. J. T. Darrow, B. B. Hu, X.-C. Zhang, and D. H. Auston, "Subpicosecond Electromagnetic Pulses from Large-Aperture Photoconducting Antennas," *Optics Letters* 15, 323-325 (1990).

#### IV.12 Lessons for Pulsed-Array Radar from Quantum Light Detection.

J. M. Myers, F. H. Madjid, and T. T. Wu, Grant N00014-89-J-1023 and Army LABCOM Contract DAAL02-89-K-0097; Research Unit 11.

Antenna arrays are potentially useful for both the transmission and the reception of trains of electromagnetic pulses. For example, a precisely controlled array of antennas driven by relativistic klystron amplifiers (RKA's) can potentially launch trains of microwave pulses (say  $N$  pulses per train) carrying a large energy flux—in Joules/m<sup>2</sup>—to strategic distances. Starting from information given to it about a target, an effective launcher will: 1) deliver adequate cumulative flux over  $N$  pulses at a distance as great as the target's, and 2) aim that flux to illuminate the target. There is a small angle by which the microwave beam axis can miss the target and still deliver adequate flux. This angle defines an allowable aiming tolerance. By virtue of energy conservation, for fixed total radiated energy, the aiming tolerance becomes tighter as the maximum flux is increased. This trade-off generates a problem in aiming. In a new paper [1], this aiming problem is formulated for an RKA-driven launcher of microwave pulses, and an approach to aiming is suggested

based on a recent study of quantum measurements [2].

For the RKA-launcher (and any other narrow-beam device), the reward for the capacity to aim the beam within a small tolerance  $\theta$  is to deliver a flux proportional to  $\theta^{-2}$ , which can be very large. The difficulty is to aim the beam within so small an angle. In testing a launcher, it is desirable to aim it at a target at a known location. Knowledge of the location, however, comes with an uncertainty. A solution has been proposed [1] that is based on using the beam itself as a radar to reduce uncertainty in the target direction. To measure the target direction accurately enough to reduce the uncertainty, one can augment the launcher by a receiver having an antenna with aperture diameter comparable to that of the launcher, so that the launcher with the adjoining receiver acts as a monopulse radar of very high angular precision. The target is in the Fresnel zone and not the far zone of this radar. One wants to locate the target quickly and accurately. A recent study of trains of light pulses [2] has shown that the time needed to make a quantum measurement of given accuracy can be reduced by varying the measurement at later pulses according to the outcomes from earlier pulses. This suggests that, in designing a radar measurement of angle, one look for a parameter to vary adaptively, pulse by pulse, guided by outcomes. The appropriate parameter here is the beamwidth, to be varied according to the dynamically estimated uncertainty in target location.

#### References:

1. F. H. Madjid, J. M. Myers, and T. T. Wu, "Lessons for Pulsed-Array Radar from Quantum Light Detection," SPIE Proceedings, Vol. 1629, Intense Microwave and Particle Beams III, 368-376 (1992).
2. F. H. Madjid and J. M. Myers, "Data-Engendered Axioms in the Quantum Theory of Optimal Measurements," *Annals of Physics*, submitted for publication.

**IV.13 The Launching of High-Power Microwave Pulses from a Relativistic Klystron Amplifier.** T. T. Wu, R. W. P. King, J. M. Myers, and H.-M. Shen, Grant N00014-89-J-1023 and Army LABCOM Contract DAAL02-92-K-0036; Research Unit 11.

A new project initiated in 1992 is concerned with the illumination of a distant target with a beam of electromagnetic waves that is characterized by both high energy and high frequency. With a suitable high-power source newly available, i.e., the Relativistic Klystron Amplifier (RKA), the problems to be solved relate to the development and design of an efficient system for transferring power from the source to a highly directive, accurately steerable, phased array of radiating elements. The construction of an apparatus for generating and projecting a very narrow, very-high-power beam of electromagnetic waves that is both adaptive and steerable is not a simple matter of design using familiar components. The problems involved require an innovative approach that makes use of a wide background of knowledge of transmission lines, multi-mode coaxial and single-mode hollow waveguides, and antenna theory including coupled horns and parabolic reflectors as elements in a steerable phased array.

Answers to the following three major technical questions are being sought: 1) How best to extract the EM energy from an RKA and transfer it efficiently to an antenna system? 2) How to design the antenna system so that it will transmit the EM energy focused into a narrow beam? 3) How to control electrically the width and direction of the EM beam and precisely direct it to a target?

Work has begun on the first question. The presently suggested way to transform the kinetic energy in a modulated electron beam in an RKA into EM energy is by means of a coaxial-line converter. The EM field generated in the coaxial line propagates in the TEM mode. This mode is not suitable for transmitting high power to the elements of the transmitting antenna, but the lowest ( $H_{10}$ ) modes in rectangular waveguides are. To use them, it is necessary to have a suitable matching

transformer whose purpose is to transmit the TEM-mode EM field from the coaxial line into the  $H_{10}$ -mode of a number of rectangular waveguides. In one design for the transformer, the dimensions of the coaxial line are greatly expanded by means of a biconical section. In the expanded coaxial line, eight fins are arranged to emerge from the inner conductor and grow gradually until they reach the outer conductor, and so divide the cross section of the coaxial line into eight sectors. These constitute separate fan-shaped waveguides which are gradually transformed into rectangular waveguides. The question arises: How much power is actually transferred to the rectangular waveguides? Because the angular distribution of the electric field in the TEM mode is uniform, the presence of the metal fins between two conductors will cause reflections. To find out how much energy is lost in the reflection and consequent mismatch, it is necessary to calculate the composite reflection coefficient.

The analysis of the RKA coaxial-line converter has been initiated. The plan for solving this problem consists of two steps: solving the eigen-mode problem in a large coaxial line with multi-fins (CLMF) of constant height, and then varying the height of the fins and solving the coupling-mode equation. The eigen-mode in a large CLMF with fins of constant height has been cast into a matrix equation which has been solved numerically. The preliminary results show that the eigenvalue changes smoothly with the height of the fins. When the height is small or zero, the eigenvalue is also small or zero, like the eigenvalue of the basic TEM-mode in a coaxial line. When the fin height is large or reaches the outer conductor, the eigenvalue is close to that of a rectangular waveguide. The analysis of the RKA converter has now advanced to the second step of formulating the coupling equations when the height of the fin is increasing or decreasing. Of primary interest is the evaluation of the reflected mode which is obtained in the solution of the coupling equations that determine the incident and reflected modes.

**IV.14 Improved Analysis of the Resonant Circular Array.** G. Fikioris, D. K. Freeman, R. W. P. King, and T. T. Wu, Grant N00014-89-J-1023, AF/RL Contract F19628-91-K-0020, and DOE Grant DE-FG02-84ER40158; Research Unit 11.

In a recent paper [1], it was shown theoretically that a large circular array of electrically short dipoles may possess very narrow resonances. The array consists of  $N$  identical, perfectly conducting, parallel, nonstaggered elements; only element 1 is center-driven, the other  $N - 1$  elements are parasitic. Subsequent investigations [2] have shown that the kernel of the  $m^{\text{th}}$  phase-sequence integral equation used in [1] does not take into account the inter-element coupling with enough accuracy for a resonant circular array. The formulation in [2] of the  $m^{\text{th}}$  phase-sequence integral equation treats self- and mutual coupling symmetrically, by averaging the mutual contribution to the vector potential over the surface of the dipole; thus the kernel takes the form of a double integral. The imaginary part of this kernel— $K_I^{(m)}(z)$  (double integral)—is, under suitable conditions, exponentially small in  $N$ , suggesting the existence of resonances that are exponentially narrow. Furthermore, this exponential smallness is independent of  $ka$ ; i.e., when  $K_I^{(m)}(z)$  (double integral) is expanded in powers of  $ka$ , each term is exponentially small.

The improved kernel developed in [2] is sufficiently complicated that an analytical study of the two-term-theory formulas is difficult and the numerical calculations involved require a large amount of computer time. More recently, an alternative, simpler version of the kernel in [2] has been proposed [3]–[5] which possesses many of its properties. It is obtained by setting  $a = 0$  in the self-term of the imaginary part of the kernel used in [1]. It is referred to as the “modified kernel.” The leading term in the asymptotic expansion of  $K_I^{(m)}(z)$  (modified) for large  $N$  is sufficiently simple to permit an analytical study of the two-term-theory formulas. The conclusions of this study (supplemented where necessary by numerical information) have been presented as a sequence of twelve basic properties relating to the kernel, the

conductances, the susceptances, and the horizontal and vertical field patterns [5]. In addition, two refinements to the modified two-term theory are described that are useful for numerical calculations whenever high accuracy is needed.

The analysis above is concerned with lossless elements. For the case of highly conducting elements—which has both theoretical and practical interest—a new formulation of the theory is necessary. In the  $m^{\text{th}}$  phase-sequence integral equation, the ohmic losses may be taken into account with a small term proportional to the internal resistance per unit length added to  $K_I^{(m)}(z)$ . By modifying  $K_I^{(m)}(z)$  in this manner throughout the formulation of the two-term theory, a new solution has been obtained. It predicts that a lossy circular array as seen by the single driven voltage at or near a resonance is equivalent to a series RLC circuit in which  $R = R_{\text{rad}} + R_{\text{loss}}$  consists of two resistances in series (where  $R_{\text{rad}}$  accounts for radiation and  $R_{\text{loss}}$  for the ohmic losses). Both of these are limiting factors for the height and quality factor of the resonance curve. The situation for a lossy array is quite different from that of a lossless array: If  $Q(m, N)$  is the quality factor in the lossless case, (a)  $Q$  rises rapidly and without limit as the number  $N$  of elements increases, and (b)  $Q$  also rises rapidly as the number  $m$  characterizing the phase-sequence resonance increases. In the case of a lossy array, the new solution predicts that: (a) As  $N$  increases,  $Q$  will first rise rapidly (while ohmic losses are negligible and radiation dominates) and then decrease linearly (when ohmic losses take over and radiation becomes small). (b) As  $m$  increases,  $Q$  will first rise rapidly (ohmic losses negligible) and then stay constant (ohmic losses dominant). Thus, the new theory predicts that it is no longer possible to obtain resonances that are as narrow as one wishes, as in the lossless case. In practical arrays, however, only moderately narrow resonances are required. Actual numerical results will soon be obtained using this new solution; the results will then be compared with the experimental data (see next topic) to determine the adequacy of the theory.

## References:

1. G. Fikioris, R. W. P. King, and T. T. Wu, "The Resonant Circular Array of Electrically Short Elements," *J. Appl. Phys.* **68**(2), 431-439 (1990).
2. D. K. Freeman and T. T. Wu, "An Improved Kernel for Arrays of Cylindrical Dipoles," presented at the 1991 IEEE/AP-S Symposium, London, Ontario, June 24-28, 1991.
3. G. Fikioris, D. K. Freeman, R. W. P. King, H.-M. Shen, and T. T. Wu, "Analytical Studies of Large Closed-Loop Arrays," SPIE Proceedings, Vol. 1407, Intense Microwave and Particle Beams II, 295-305 (1991).
4. G. Fikioris, R. W. P. King, H.-M. Shen, and T. T. Wu, "Novel Resonant Circular Arrays," presented at the Progress in Electromagnetics Research Symposium (PIERS), Cambridge, MA, July 1-5, 1991.
5. G. Fikioris, R. W. P. King, and T. T. Wu, "Improved Analysis of the Resonant Circular Array of Electrically Short Elements," *J. Appl. Phys.*, submitted for publication.

## IV.15 Experimental Studies of Resonances in a Large Circular Array.

G. Fikioris, Grant N00014-89-J-1023 and Army LABCOM Contract DAAL02-89-K-0097; Research Unit 11.

In order to verify the existence of the theoretically predicted, extremely sharp resonances that occur in a circular array with many identical elements but only one driven, experimental investigations of such an array have been carried out. Results from the first experiment have been reported previously [1]; they showed that resonance does occur. They also demonstrated how sensitively the resonance properties of the array depend on the precise mechanical implementation. To agree with theory, the elements should be identical, perfectly vertical, and positioned exactly on the circle. Any slight deviation from these ideal conditions affects the measurements significantly, especially the resonant admittance values. In the original experiment, a number of adjustments to the array were needed in order to achieve close agreement between the measurements and the end-corrected theory [2]. These adjustments included the use of a connecting chain to improve the accuracy of the interelement spacing, the addition of a thin disk at the base of each element to keep it vertical, and low-resistance conductive cement between each disk and the ground

plane.

To improve the electrical contact between the individual elements and the ground plane, and to remove any ambiguity in the element length caused by the presence of the thin disk at the base of each element, a second experiment was designed and constructed [3]. In the new experiment, the choice of parameters (i.e., the height  $h$  and radius  $a$  of each element and the distance  $d$  between adjacent elements) is based on the results of the modified two-term theory, so that larger currents around the array should be obtained. The setup consists of 89 parasitic elements and one driven element, equally spaced around a circle of 40-in. diameter. The single driven element is the extension of the inner conductor of a coaxial transmission line. The parasitic elements are thin-walled brass cylinders that are securely fastened (screwed) onto the ground plane to improve the electrical contact with the ground plane. The tolerances in the location of the holes was  $\pm 0.001$  in. in the radial positioning and  $\pm 0^\circ 0' 1''$  in the angular positioning. The monopoles were machined by a lathe out of 1/4-in. brass rods. The tolerance in the heights of the parasitic elements was  $\pm 0.001$  in. The walls were made quite thin so that the tubular elements of the theory could be realized.

The purpose of the experiment is to calculate the driving-point admittance of the array from swept-frequency measurements of voltages at fixed points along the transmission line. During the current reporting period, different measuring methods have been developed and a series of measurements have been carried out. Certain difficulties inherent in the measurement of rapidly varying admittances were encountered. These have been analyzed and several approaches to overcoming these difficulties have been proposed. Despite the difficulties, it has been shown that narrow resonances occur and that the experimental frequency-response curves show many of the qualitative features predicted by theory. Excellent agreement has been obtained between the experimentally determined resonant frequencies and

those predicted by the two-term theory.

The finite conductivity of the elements is a significant limiting factor in the large values of current that can be attained in practice. The existing theory does not take the finite conductivity into account. Investigations are in progress to develop a theory that includes the effect of ohmic losses. Once this has been accomplished, much better agreement between theory and experiment is expected in regard to the values of the currents at resonance. On the other hand, it is anticipated that ohmic losses will have a negligible effect in shifting the theoretically predicted resonant frequencies.

#### **References:**

1. H.-M. Shen, "Experimental Study of the Resonance of a Circular Array," SPIE Proceedings, Vol. 1407, Intense Microwave and Particle Beams II, 306-315 (1991).
2. G. Fikioris, D. K. Freeman, R. W. P. King, H.-M. Shen, and T. T. Wu, "Analytical Studies of Large Closed-Loop Arrays," SPIE Proceedings, Vol. 1407, Intense Microwave and Particle Beams II, 295-305 (1991).
3. G. Fikioris, R. W. P. King, H.-M. Shen, and T. T. Wu, "Novel Resonant Circular Arrays," presented at the Progress in Electromagnetics Research Symposium (PIERS), Cambridge, MA, July 1-5, 1991.

#### **IV.16 Properties of Closed-Loop Arrays of Quantum Mechanical and Electromagnetic Interactions. D. K. Freeman and T. T. Wu, Grant N00014-89-J-1023 and DOE Grant DE-FG02-84ER40158; Research Unit 11.**

This research project has now been completed. The doctoral thesis of D. Kent Freeman [1] has been defended successfully and the Ph.D. degree awarded to Dr. Freeman in June 1992. The purpose of this study has been to trace the phenomenon of extremely narrow resonances in closed-loop arrays from its simplest manifestation in arrays of Fermi pseudopotentials in quantum mechanics to its current status as a means of designing novel electromagnetic antenna arrays. The first rigorous investigation of resonances in closed-loop arrays was carried out by

Grossmann and Wu [2] using the circular array of uniformly spaced Fermi pseudopotentials. The Fermi pseudopotential is the simplest possible nontrivial scatterer for the Schrödinger equation. It is a convenient model for studying array phenomena that occur in classical electromagnetism since its mathematical formalism is consistent and explicitly solvable. This simplification is justified by the observation that many interesting array phenomena depend only on the geometry defined by the positions of the scattering centers and not on the details of the particular interaction. It was found that, as the number of pseudopotentials tends to infinity while the arc-length spacing is held constant, such an array admits resonances whose widths tend to zero *exponentially*. This result was the foundation for the present work.

Although the pseudopotential provides the simplest framework for studying the resonance phenomenon of closed loops, it has two drawbacks. First, the pseudopotential, being a point interaction, lacks structure; thus, it is impossible to determine what effect the range of the interaction has on the resonances. To address this question, the pseudopotential has been generalized to an interaction with nonzero range by studying the self-adjoint integral-operator potential of finite rank. In a new paper [3], it is shown that a uniformly spaced infinite linear array of such potentials can admit resonances whose widths tend to zero exponentially as the number of potentials tends to infinity while the arc-length spacing remains constant. Additionally, it is demonstrated that the pseudopotential can be derived from such an integral-operator potential as an appropriate limit.

The second drawback of the pseudopotential is that it is not clear if results obtained using the pseudopotential are applicable to antenna arrays in classical electromagnetism. Two models have been developed for studying this phenomenon directly within the context of the Maxwell equations. The first of these is the pseudodipole, which was introduced by Wu [4] as the simplest possible nontrivial scatterer in the context of Maxwell's equations. Like the pseudopotential, the pseu-

dodipole is a point interaction. Therefore, if the pseudodipole is to approximate a physical dipole, the physical dipole should be, in some sense, small. Moreover, in order for such a small object to produce a significant scattered field, one expects that it must be resonant. This suggests the idea of taking a center-loaded cylindrical dipole, and letting its size tend to zero while simultaneously adjusting the load reactance in order to keep the magnitude of the scattered field constant. In a recent paper [5], it is shown that for an incident plane-wave, this procedure results in a scattered field which is precisely the scattered field of a pseudodipole. The circular array of uniformly spaced pseudodipoles has also been studied [6]. The implications of this study are used to redefine the pseudodipole in a more mathematically consistent manner, as well as to further elucidate its connection with the physical cylindrical dipole.

The second of the two electromagnetic models developed in [1] is a new formulation for studying the cylindrical dipole directly. Perhaps the most useful method of analysis for arrays of cylindrical dipoles is the "two-term theory" [7]. This method has the advantage of producing relatively simple closed-form solutions for the self- and mutual admittances while providing remarkable agreement with experimental results. The two-term theory is not accurate enough, however, to predict correctly the extremely narrow resonances in closed-loop arrays consisting of a large number of dipoles. This problem has been addressed by introducing an improved kernel [8] governing the interaction between cylindrical dipoles. This kernel is inherently more accurate than the one in [7] and possesses the properties required to predict correctly the narrow resonances in closed-loop arrays. Finally, in order to gain a better understanding of why the two-term theory works so well, a new formulation of this theory based on the variational principle has been developed [9]. It is observed that the two-term theory can be further improved by incorporating an end correction into the parasitic-dipole current. Combined with the improved ker-

nel, this new formulation provides a simple, mathematically sound framework for studying resonances in closed-loop arrays of cylindrical dipoles.

#### References:

1. D. K. Freeman, "Extremely Narrow Resonances in Closed-Loop Arrays of Quantum Mechanical and Electromagnetic Interactions," Ph.D. Thesis, Harvard University (1992).
2. A. Grossmann and T. T. Wu, "A Class of Potentials with Extremely Narrow Resonances," *Chinese Jour. Phys.* **25**(1), 129-139 (1987).
3. D. K. Freeman, "Generalization of the Pseudopotential to an Interaction with Nonzero Range," *J. Math. Phys.* **33**(6), 2215-2227 (1992).
4. T. T. Wu, "Fermi Pseudopotentials and Resonances in Arrays," pp. 293-306 in *Resonances—Models and Phenomena: Proceedings, Bielefeld 1984*, S. Albeverio, L. S. Ferreira, and L. Streit, Eds., Springer-Verlag, Berlin (1984).
5. D. K. Freeman, "The Pseudodipole as the Limit of a Resonant Cylindrical Dipole," *J. Math. Phys.* **32**(7), 1961-1964 (1991).
6. D. K. Freeman, "Resonances and Stability in Arrays of Pseudodipoles," in preparation.
7. R. W. P. King, R. B. Mack, and S. S. Sandler, *Arrays of Cylindrical Dipoles*, Cambridge University Press, New York (1968).
8. D. K. Freeman and T. T. Wu, "An Improved Kernel for Arrays of Cylindrical Dipoles," presented at the 1991 IEEE/AP-S Symposium, London, Ontario, June 24-28, 1991.
9. D. K. Freeman and T. T. Wu, "Variational-Principle Formulation of the Two-Term Theory for Arrays of Cylindrical Dipoles," in preparation.

**IV.17 Experimental Study of a Noncircular Array.** T. T. Wu, R. W. P. King, and H.-M. Shen, Grant N00014-89-J-1023, AF/RL Contract F19628-91-K-0020, and Army LABCOM Contract DAAL02-89-K-0097; Research Unit 11.

Circular closed-loop arrays of parallel dipoles have been found to have interesting properties; they have extremely narrow resonances and the radiation pattern is also extremely narrow. Unfortunately, the directivity is poor, i.e., the pattern has many equal and equally spaced lobes. There is reason to think that, by deforming these arrays from the circular shape, better directivity can be obtained. The search

for closed-loop arrays with high directivity is a challenging task, however, since there is no ready theory or rule to follow. It is extremely difficult to develop an analytical method for determining the currents on the elements of an array with arbitrary shape since this involves solving a large number of coupled integral equations.

What is needed is a qualitative theory that can determine the currents approximately in an easy but physically sound way. Based on an understanding of the Yagi-type parallel-dipole array, it has been assumed that the EM wave travels around the curved line guided by the elements with their currents in a manner characteristic of a traveling wave. The propagation constant is assumed to be the same as that of a straight-line array, provided the radius of curvature is much larger than the wavelength. An experiment has been carried out to verify this traveling-wave assumption [1]. The noncircular array is obtained by displacing only a small number of elements from the original circular shape. This choice of shape was selected initially simply for convenience in performing the experiment, since it is important to keep the spacing  $d$  between adjacent elements equal. It was found later that such a shape has inherent advantages for producing higher directivity. The detailed experimental investigation has confirmed that a traveling wave is preserved in a curved parallel-dipole array. The small energy loss or amplitude decay associated with a curved array is negligible for pattern calculation.

Once the currents on the elements have been determined, calculating the radiation pattern is straightforward. However, there is the problem of how to search for shapes that are likely to produce higher directivity. Since there are innumerable possibilities, it is hopeless to find them by random choice. Consequently, it is necessary to find some rules which can guide the search. The traveling-wave assumption described above has been used to study a variety of closed-loop arrays, and guidelines concerning radiation from a traveling-wave source have been formulated [1]. Based on these, relations have been established between individual elements (local

sources) in the array and individual lobes (local targets) in the pattern. It is found that a change in the local source can cause a change in its related local target. Thus, it is possible to locate the sources of the individual lobes and then adjust these sources to improve the pattern. With this method, patterns have been improved significantly; the main lobe has been increased and the side lobes have been substantially reduced.

#### Reference:

1. H.-M. Shen, "Experimental Study of a Noncircular Array," SPIE Proceedings, Vol. 1629, Intense Microwave and Particle Beams III, 281-297 (1992).

**IV.18 Plasma Waveguide: A Concept to Transfer EM Energy in Space.**  
H.-M. Shen, Grant N00014-89-J-1023 and Army LABCOM Contract DAAL02-89-K-0097; Research Unit 11.

It has been shown that electromagnetic (EM) energy originating at a source in upper space can be transferred efficiently through a plasma waveguide [1]. Such a waveguide consists of a cylindrical vacuum core surrounded by a plasma cladding medium, which can be generated in upper space by a hollow laser beam [2]. An experiment demonstrating an actual 95-meter long laser-generated plasma channel was reported in 1985 by Livermore National Laboratory [3]. The analysis and survey show that the plasma waveguide at high frequencies ( $\omega \gg \omega_p$ ) has many excellent performance characteristics for transporting a microwave pulse. The EM pulses that travel in such a waveguide are dispersion-free and have a speed close to that of light. In other words, the EM pulses can follow the laser-generated plasma channel and, like current pulses in a wire, "move" at the speed of light.

In the first model of the plasma waveguide [1], the plasma cladding was assumed to extend transversely to infinity. Therefore, the guided modes are loss-free. If the cladding is finite, there will be an energy loss from the outside surface of the cladding. To study this effect, an analysis of the plasma waveguide with finite

thickness was carried out [4] and the coefficient of the energy decay calculated. It was found that most of the properties for the case of infinite thickness are retained for the plasma waveguide with finite thickness: the guided modes  $HE_{n,m}$  at high frequencies are split into two frequency-independent modes, a high- $n$  mode and a low- $n$  mode; the characteristic equation at high frequencies is also split into two equations; the eigenvalue  $x$  (although now a complex number) is constant and much smaller than  $ka$ ; the EM pulse propagates with constant profile and shape and at the speed of light; and the loss due to the conductivity of the plasma and the anisotropic effect due to the earth's magnetic field are small.

The main concern of the new analysis is the loss from the outside surface of the plasma tube. It is natural to suspect the loss to be significant since the field does not decrease fast enough transversely. For instance, the field on the surface at  $r = 2a$  is still 7% of the maximum field. However, the results of this analysis turn out to be quite different. For the case of finite thickness, the eigenvalue  $x$  of the characteristic equation becomes a complex number. The imaginary part  $x_I$  is much smaller than the real part  $x_R$ . It decreases exponentially with the thickness of the cladding. Especially for high-frequency operation—since the EM wave itself has better “directivity”—the plasma tube has the ability to hold most of the energy within the tube, i.e., the loss is surprisingly small.

#### References:

1. H.-M. Shen, “Plasma Waveguide: A Concept to Transfer EM Energy in Space,” *J. Appl. Phys.* **69**(10), 6827–6835 (1991).
2. APS Study Group, “APS Study: Science and Technology of Directed Energy Weapons,” *Rev. Mod. Phys.* **59**(3), Part II, Sec. 4.2, S71–S79 (1987).
3. D. S. Prono, “Recent Progress of the Advanced Test Accelerator,” *IEEE Trans. Nucl. Sci.* **NS-32**, 3144–3148 (1985).
4. H.-M. Shen and H.-Y. Pao, “The Plasma Waveguide with a Finite Thickness of Cladding,” *J. Appl. Phys.* **70**(11), 6653–6662 (1991).

## ANNUAL REPORT OF PUBLICATIONS/PATENTS/PRESENTATIONS/HONORS

### a. Papers Submitted to Refereed Journals (and not yet published)

R. W. P. King and S. S. Sandler, "The Detection of Dielectric Spheres Submerged in Water," *IEEE Trans. Geosci. & Remote Sensing* (accepted). (Partial support from the Small Business Administration under the SBIR Program in collaboration with Geo-Centers, Inc., and the U.S. Army Medical Branch.)

R. W. P. King, "The Propagation of a Gaussian Pulse in Sea Water and Its Application to Remote Sensing," *IEEE Trans. Geosci. & Remote Sensing*. (Partial support from Raytheon Co. under Contract N61533-90-C-0080 with ONR, Annapolis Detachment.)

R. W. P. King, "The Propagation of a Low-Frequency Burst in Sea Water and Its Application to Remote Sensing," *IEEE Trans. Geosci. & Remote Sensing*. (Partial support from Raytheon Co. under Contract N61533-90-C-0080 with ONR, Annapolis Detachment.)

R. W. P. King, "Scattering of a Cylinder Submerged in the Ocean: The Propagation of a Low-Frequency Rectangular Pulse," *Radio Sci.* (Partial support from Raytheon Co. under Contract N61533-90-C-0080 with ONR, Annapolis Detachment.)

R. W. P. King and T. T. Wu, "The Propagation of a Radar Pulse in Sea Water," *J. Appl. Phys.* (Partial support from Raytheon Co. under Contract N61533-90-C-0080 with ONR, Annapolis Detachment.)

G. Fikioris, R. W. P. King, and T. T. Wu, "Improved Analysis of the Resonant Circular Array of Electrically Short Elements," *J. Appl. Phys.* (Partial support from AF/RL Contract F19628-91-K-0020.)

F. H. Madjid and J. M. Myers, "Data-Engendered Axioms in the Quantum Theory of Optimal Measurements," *Annals of Physics*. (Partial support from Army LABCOM Contract DAAL02-89-K-0097.)

### b. Papers Published in Refereed Journals

R. W. P. King, "Electromagnetic Field of Dipoles and Patch Antennas on Microstrip," *Radio. Sci.* 27(1), 71-78 (1992).

R. W. P. King, "The Circuit Properties and Complete Fields of Horizontal-Wire Antennas and Arrays Over Earth or Sea," *J. Appl. Phys.* 71(3), 1499-

1508 (1992).

M. F. Brown and J. M. Myers, "Scattering of Electromagnetic Missiles by Convex Metal Objects," *J. Appl. Phys.* 70(11), 7176-7178 (1991). (Partial support from Army LABCOM Contract DAAL02-89-K-0097.)

D. K. Freeman, "The Pseudodipole as the Limit of a Resonant Cylindrical Dipole," *J. Math. Phys.* 32(7), 1961-1964 (1991). (Partial support from DOE Grant DE-FG02-84ER40158.)

D. K. Freeman, "Generalization of the Pseudopotential to an Interaction with Nonzero Range," *J. Math. Phys.* 33(6), 2215-2227 (1992). (Partial support from DOE Grant DE-FG02-84ER40158.)

H.-M. Shen and H.-Y. Pao, "The Plasma Waveguide with a Finite Thickness of Cladding," *J. Appl. Phys.* 70(11), 6653-6662 (1991). (Partial support from Army LABCOM Contract DAAL02-89-K-0097.)

**d. Books (and sections thereof) Published**

R. W. P. King, M. Owens, and T. T. Wu, *Lateral Electromagnetic Waves: Theory and Applications to Communications, Geophysical Exploration, and Remote Sensing*, Springer-Verlag, New York (1992).

**h. Contributed Presentations at Topical or Scientific/Technical Society Conferences**

J. M. Myers and H.-M. Shen, "Experiments Using Laser-Triggered Electrical Discharges to Generate Electromagnetic Missiles," SPIE Proceedings, Vol. 1629, Intense Microwave and Particle Beams III, 274-280 (1992). (Partial support from Army LABCOM Contract DAAL02-89-K-0097.)

H.-M. Shen, "Experimental Study of a Noncircular Array," SPIE Proceedings, Vol. 1629, Intense Microwave and Particle Beams III, 281-297 (1992). (Partial support from AF/RL Contract F19628-91-K-0020 and Army LABCOM Contract DAAL02-89-K-0097.)

F. H. Madjid, J. M. Myers, and T. T. Wu, "Lessons for Pulsed-Array Radar from Quantum Light Detection," SPIE Proceedings, Vol. 1629, Intense Microwave and Particle Beams III, 368-376 (1992). (Partial support from Army LABCOM Contract DAAL02-89-K-0097.)

**i. Honors/Awards/Prizes**

R. W. P. King, 1991 Distinguished Service Award, from the IEEE Antennas and Propagation Society.

**j. Graduate Students and Post-Doctorals Supported under the JSEP  
for the Year Ending 30 June 1992**

Mr. V. Houdzoumis.



## V. SIGNIFICANT ACCOMPLISHMENTS REPORT

### V.1 Competitive Analog Neural Networks for Translation-Invariant Feature Detection. F.R. Waugh and R.M. Westervelt; Research Unit 5, SOLID STATE ELECTRONICS.

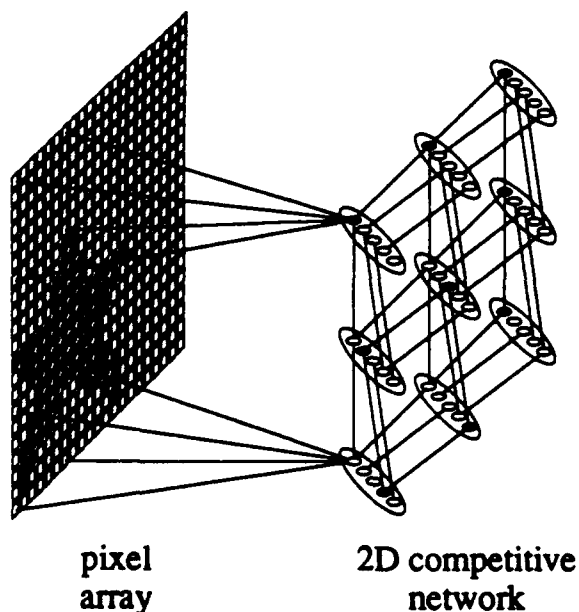
Competition among a group of neurons is common in pattern-recognizing neural networks. Competitive winner-take-all networks can mimic associative memory behavior if each neuron performs a dot-product of the network input with the pattern that the neuron represents. Much less common are *networks* of groups of competing neurons, which are functionally similar to networks of interconnected associative memories. Fukushima's neocognitron is a feed-forward example of such a network.

We have studied the dynamics of recurrent networks of interconnected groups of competing analog neurons. We have shown that, with symmetric interconnections and discrete-time, parallel updating, these networks are stable when the slopes of the neuron input-output transfer functions are sufficiently small. When configured in a two-dimensional, locally-connected architecture (see accompanying figure), these networks can perform translation-invariant feature detection on visual images. Each neuron in a competing group represents a fragment of the feature to be detected, and neurons receive inputs both from a localized region of a pixel array and from neurons in neighboring clusters. Interconnections between clusters enable the networks to reconstruct complete features from their constituent fragments, with translation invariance on the fragment length scale.

Competition can be implemented naturally in analog electronics by forcing competing neurons to share a limited resource, such as the current through a common wire. Moreover, competition can greatly reduce the density of neural interconnections in visual processing applications, because neurons communicate information about whole features rather than individual pixels.

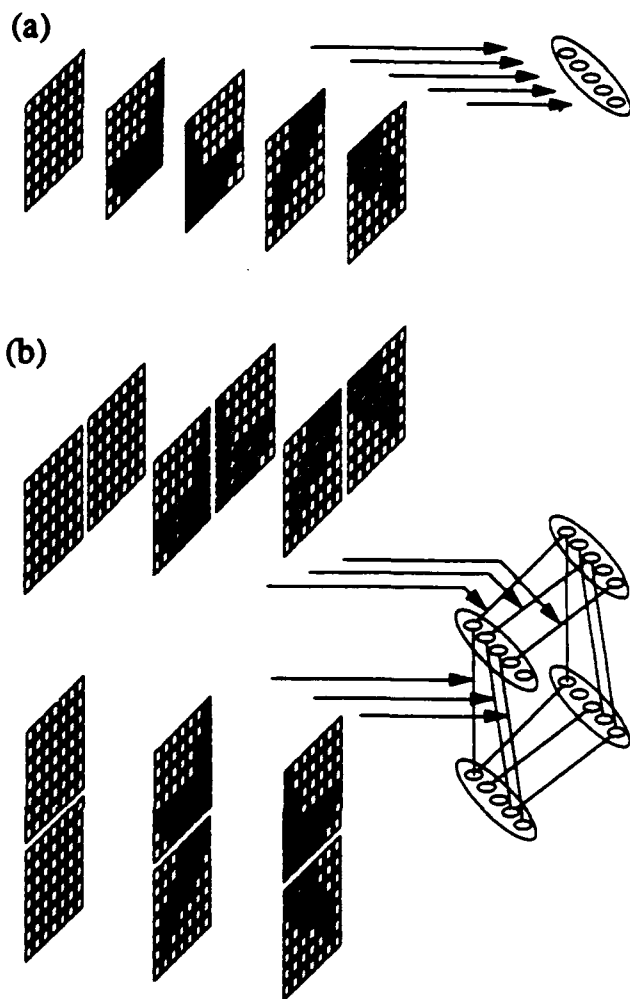
# COMPETITIVE ANALOG NEURAL NETWORKS FOR TRANSLATION-INVARIANT FEATURE DETECTION

## architecture

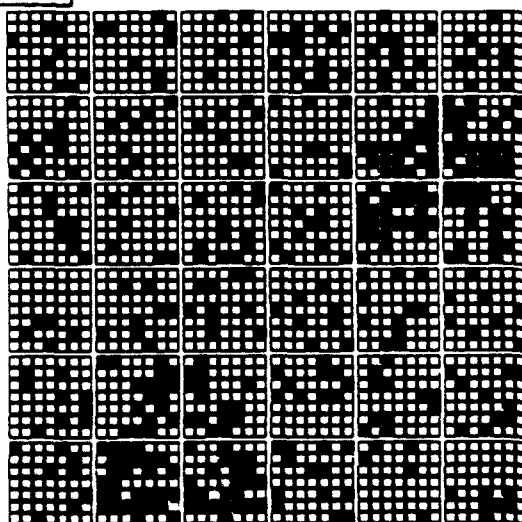


(a) competing neurons represent pattern fragments

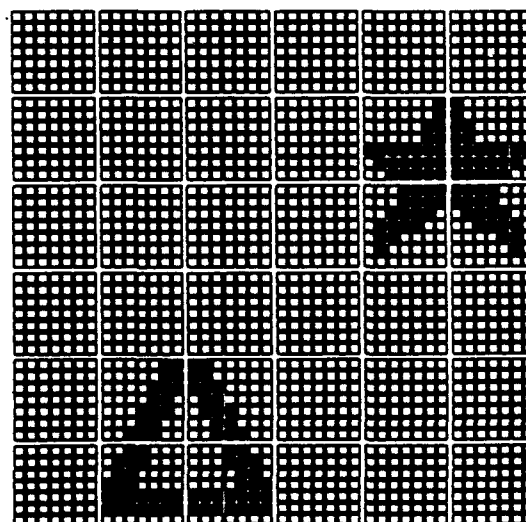
(b) connections between neurons store relations among pattern fragments



## performance



initial condition



final attractor

**V.2 A Novel Resonant Array of Parallel Dipoles with Unique and Useful Properties.** R. W. P. King, T. T. Wu, D. K. Freeman, G. Fikioris, and H.-M. Shen; Research Unit 11, ELECTROMAGNETIC PHENOMENA.

A theoretical and experimental study has been made of the remarkable properties of a circular array of a large number  $N$  of parallel dipoles with only one element driven. The length and radius of each tubular element and the distance between adjacent elements have been determined analytically for the particular sets of values for which the entire array resonates. A large number of possible modes exists. For each, the currents in the elements attain extremely large amplitudes with phase relations determined by the particular mode. The driving-point impedance of the single driven element is a pure resistance at each resonance. The experimental array consists of 90 elements and the predictions of the theory have been verified over a range of frequencies that includes a sequence of many resonant modes.

The field pattern of the highest mode (in which the phases of the currents in adjacent elements differ by exactly  $180^\circ$ ) consists of a circle of 90 pencil-like spikes, each with extremely narrow beam width in both vertical and horizontal planes. This mode has an interesting application as a beacon. When rotated at a desired frequency—e.g., 1 rpm—the array sends out 90 pulses per minute in all directions. If a unidirectional pattern is desired, the 90 elements can be rearranged in a serpentine manner with the condition of resonance preserved. An optimum shape and design leading to a true supergain pattern remains to be determined. In another important modification, a single omnidirectional pancake-like pattern with an extremely narrow vertical beam width can be obtained. When located over the earth or sea, this generates a powerful omnidirectional surface wave with virtually no sky wave. Application to a ground-wave over-the-horizon radar is indicated.

# Significant Accomplishments for FY1992

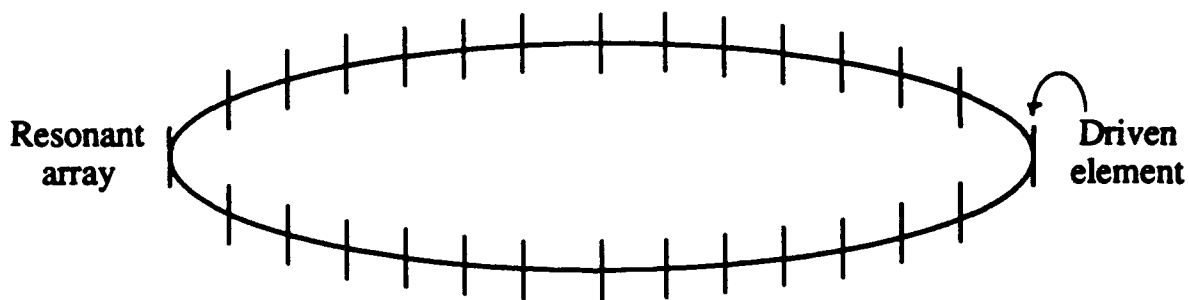
Research Unit 11 on ELECTROMAGNETIC PHENOMENA

Harvard University—JSEP Grant N00014-89-J-1023

Principal Investigator: Professor Tai Tsun Wu

## A Novel Resonant Array of Parallel Dipoles with Unique and Useful Properties

Highly accurate formulas have been developed and verified experimentally for the properties of a closed loop of a large number of dipoles of which only one or two are driven.



### Unusual Properties in Resonant Mode:

- Driving-point impedance: Very small pure resistance.
- Field patterns governed by shape of loop and excitation.
  - $N$  radial spikes; rotate for use as beacon.
  - Single, highly directional beam.
  - Omnidirectional, very flat, pancake-like pattern; deploy array in space for communication; erect over earth or sea for ground-wave communication, or over-the-horizon radar in  $10^8$  km range.